ANKARA YILDIRIM BEYAZIT UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

INCREMENTAL FUZZY CONTROL OF BLDC MOTOR ON FPGA FOR MISSILES

M.Sc. Thesis by

Murat ÖZEV

Department of Electrical and Electronics Engineering

February, 2020

ANKARA

INCREMENTAL FUZZY CONTROL OF BLDC MOTOR ON FPGA FOR MISSILES

A Thesis Submitted to

The Graduate School of Natural and Applied Sciences of

Ankara Yıldırım Beyazıt University

In Partial Fulfillment of the Requirements for the Degree of Master of Science in Electrical and Electronics Engineering, Department of Electrical and Electronics Engineering

by

Murat ÖZEV

February, 2020

ANKARA

M.Sc. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled "**INCREMENTAL FUZZY CONTROL OF BLDC MOTOR ON FPGA FOR MISSILES**" completed by **MURAT ÖZEV** under supervision of **PROF. DR. AHMET KARAARSLAN** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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Supervisor

Prof. Dr. İres İSKENDER

Jury Member

Asst. Prof. Dr. Gökhan Koray GÜLTEKİN

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ACKNOWLEDGMENTS

I would like to take this opportunity to thank my supervisor, Prof. Dr. Ahmet KARAARSLAN, for his guidance, moral support and advices. He spent so much time and effort in making this thesis an accomplished task. Thanks to for his great contribution on this work that I could complete my thesis.

I also wish to thank Serdar UYGUR, Ali YILMAZKOCLAR, Osman Volkan KARACA and Dr. Salih ZENGİN for their great support and advices.

I also wish to thank TÜBİTAK SAGE; this work was supported from the initial stages to the end.

2020, 07 February **Murat ÖZEV**

INCREMENTAL FUZZY CONTROL OF BLDC MOTOR ON FPGA FOR MISSILES

ABSTRACT

In this study, the comparison of Incremental Fuzzy and Proportional Integral (PI) control methods on Field Programmable Gate Array (FPGA) is investigated for gimbals and fins of missiles which include Brushless Direct Current (BLDC) motors. The BLDC motors are widely used in two important parts of guided missiles due to their high performance. Firstly, Gimbals usually include two BLDC motors and seeker camera. These motors provide two axis seeker camera motions, so the missiles can trace the target. Secondly, missiles can be guided to intended direction by BLDC motors that are used in the control system of fins. According to these roles, the control of BLDC motors is very important for missiles and defense industry. Therefore, the performances of Incremental Fuzzy and PI control methods on BLDC motors were analyzed in detail in terms of both simulation and experimental study. The simulation results were obtained by using Matlab/Simulink program. FPGA based electronic board was used for experimental results. The experimental results are compatible with simulation results. It is proved that Incremental Fuzzy control method is more reliable and stable than PI control method. So implementation of Incremental Fuzzy control method improves the missiles performance.

Keywords: Incremental fuzzy control, PI control, current control, position control, missile, gimbal, fin, FPGA

FÜZELER İÇİN FPGA'DE BLDC MOTORUN ARTIRIMLI FUZZY KONTROLÜ

ÖZ

Bu çalışmada, füzelerin BLDC motorları içeren kardanları ve kanatçıkları için FPGA üzerinde Artırımlı Fuzzy ve PI kontrol metotlarının karşılaştırılması araştırılmıştır. BLDC motorları, yüksek performansları nedeniyle güdümlü füzelerin iki önemli bölümünde yaygın olarak kullanılmaktadır. İlk olarak, kardanlar genellikle iki BLDC motor ve arayıcı kamera içerir. Bu motorlar arayıcı kameranın iki eksende hareketi sağlar, böylece füzeler hedefi izleyebilir. İkinci olarak, füzeler kanatçıkların kontrol sisteminde kullanılan BLDC motorları tarafından istenen yöne yönlendirilebilir. Bu görevlere göre, BLDC motorlarının kontrolü füzeler ve savunma endüstrisi için çok önemlidir. Bu nedenle, Artırımlı Fuzzy ve PI kontrol metotlarının BLDC motorlarındaki performansı, hem simülasyon hem de deneysel çalışma açısından ayrıntılı olarak analiz edildi. Simülasyon sonuçları Matlab/Simulink programı kullanılarak elde edildi. Deneysel sonuçlar için FPGA tabanlı elektronik kart kullanıldı. Deneysel sonuçlar simülasyon sonuçlarıyla uyumludur. Artırımlı Fuzzy kontrol yönteminin PI kontrol yönteminden daha güvenilir ve kararlı olduğu kanıtlanmıştır. Bu nedenle, Artırımlı Fuzzy kontrol yönteminin uygulanması füze performansını artırır.

Anahtar Kelimeler: Artırımlı Fuzzy kontrol, PI kontrol, akım kontrolü, pozisyon kontrolü, füze, kardan, kanatçık, FPGA

CONTENTS

NOMENCLATURE

Acronyms

ADC	Analog to Digital Converter
BLDC	Brushless Direct Current
DSP	Digital Signal Processing
EMI	Electromagnetic Interference
FPGA	Field Programmable Gate Array
IC	Integrated Circuit
SPI	Serial Peripheral Interface
PI	Proportional Integral
PWM	Pulse Width Modulation

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CHAPTER 1

INTRODUCTION

Motion control systems are important parts of defense industry including guided missiles [1]. BLDC motors are the most preferred motors for motion control systems due to the their good mechanic reliability, high efficiency and EMI compatibility [2]. But controlling of BLDC motors are complicated in terms of electronic circuit, control algorithms and digital computations [3].

There are too many controllers for BLDC motors. Most used of them is PI controllers because of their ease of design and basic structure. More than 90% of the controller methods include PI controller [4]. PI controller algorithm is basic, consistent, high reliability and simple adjustment for linear systems. However, constant PI parameters are not good solutions for nonlinear systems. But tuning parameters of PI controller are not easy, so it is too difficult to reach the optimum situation [5].

Fuzzy logic has become a popular method in many controller designs. Incremental Fuzzy control method is a better method for controlling complicated and nonlinear systems. This method can give better rising time, fast dynamic response, robustness and efficient control thanks to Fuzzy tuning. It has verified efficient method for non-linear, complicated and imprecisely described systems which standard control methods are inapplicable or impossible [5]. There are a lot of subclasses of fuzzy tuning. Incremental Fuzzy Control, Fuzzy Self Tuning of Single Parameter, Fuzzy Gain Scheduling, Fuzzy Set-Point Weight Tuning [4]. In this study, Incremental Fuzzy Control method is used as a current controller.

There are different methods to implement controllers. One of them includes DSP and FPGA [6]. In this method, complex electronic boards have to be used because of using both FPGA and DSP chips. Complex control algorithms for position and current control are implemented on DSP chips. But DSP chips cannot operate at a high frequency for current feedback and position control at the same time. Also other disadvantage of this method is limited capacity of DSP [7].

Another method of BLDC motor controller implementation is based on the microcontrollers [8-11]. There are specified microcontrollers which are produced for motor controller. But these microcontrollers have restricted source of position feedback, current feedback and PWM channels. In this method, the numbers of controlled motors are limited because of these restricted resources.

Most preferred method is FPGA-based design of motor control [12]. Property of the FPGAs, such as programmability, easy design cycle, marketable, efficiency and sufficient density, increase the usage of FPGAs [13]. BLDC motor controllers which are implemented on FPGA are less complicated and more reliable than the DSP and FPGA based designs and more flexible than microcontroller based controllers [2]. Also FPGA fills the gap between software and hardware; achieve higher performance and flexibility than software [14]. According to these advantages, we used FPGA based electronic board to implement motor controller.

In this study, BLDC motors are introduced in Chapter 2. After that PI and Incremental Fuzzy control methods are detailed in Chapter 3. Then the operation principle of these control are given in Chapter 4. The simulation and experimental results are studied in Chapter 5 and 6 respectively. The conclusion is given in the last chapter.

CHAPTER 2

BLDC MOTORS

Motors convert electrical energy to mechanical energy. There are many type of electrical motors. BLDC motor is one of them. BLDC motor is a permanent magnet synchronous electric motor which is driven by DC current and it is controlled with electronically commutation system instead of a mechanical commutation system. BLDC motor works electrical commutation with permanent magnet rotor and a stator which is a sequence of coils. In this type of motor, permanent magnet rotates and current carrying conductors are fixed.

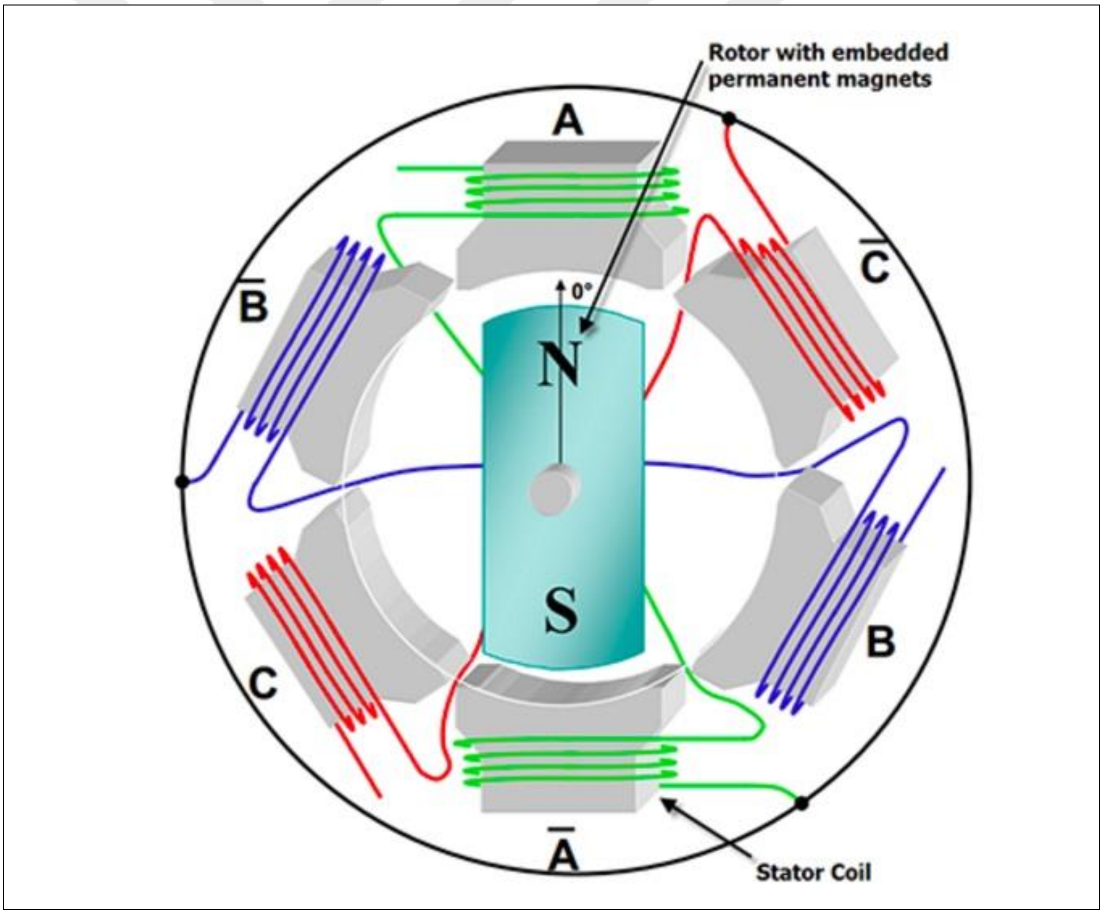

Figure 2.1 Structure of BLDC motor

There are some advantages of BLDC motors:

- There is no mechanical commutator and related problems.
- High efficiency because of the permanent magnet rotor.
- High speed operation on all conditions thanks to the lack of brushes that limits the speed.
- Smaller and lighter mechanical structure than both brushed type DC and induction AC motors.
- Long life whereby absence of maintenance is required for commutator system.
- High dynamic response due to the fact that low inertia and carrying windings in the stator.
- Low electromagnetic noise.
- Low working noise because of brushless structure.

Also there are some disadvantages of BLDC motors:

- High cost.
- Complex electronic board required control this motor.
- Requires complex drive circuitry.
- Need of additional sensors such as hall sensor, encoder etc.

2.1 Structure of BLDC Motor

BLDC motor is composed of a three winding stator coils and permanent magnetic rotor. The structure of BLDC motor most similar to the AC motor. The construction of a typical three-phase BLDC motor is shown on Figure 2.2.

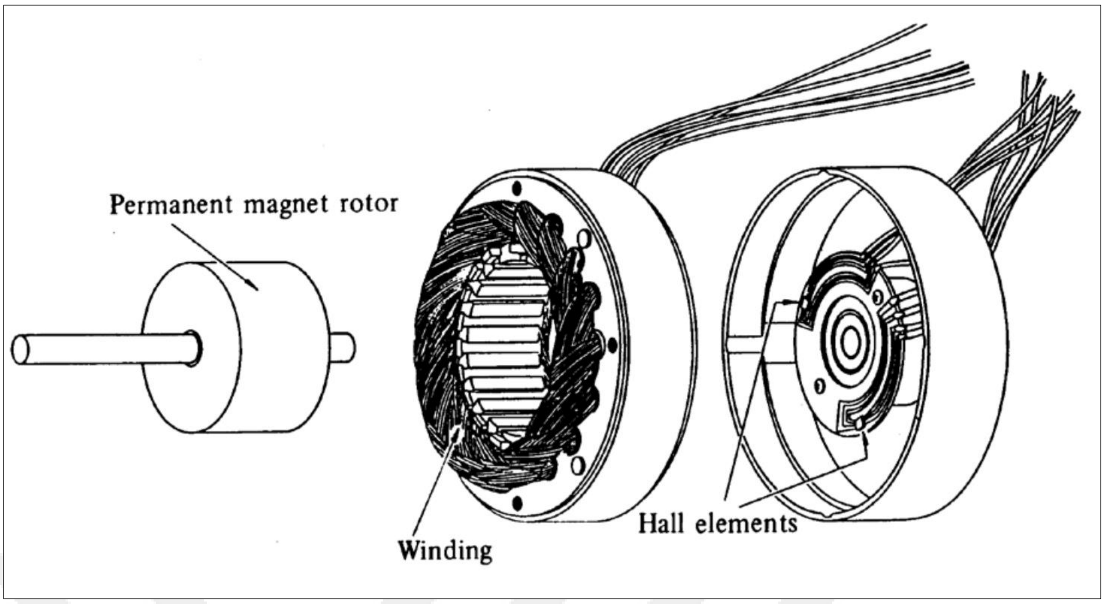

Figure 2.2 Inside of the BLDC motor

Stator is a static part which is includes windings. The stator number depends on the winding shape, number of phase and the rotor poles. Stator of a BLDC motor made up of stacked steel laminations to carry the windings. These windings are placed in slots which are axially cut along the inner periphery of the stator. The stator should be chosen with the correct voltage rating which is depending on the power supply capability.

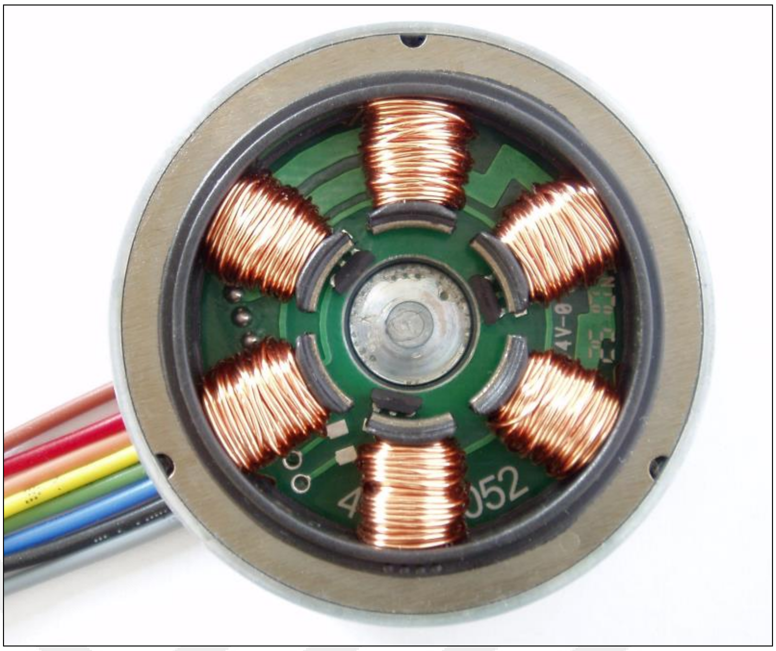

Figure 2.3 Stator windings of BLDC motor

Rotor is the rotating part. The rotor is composed with permanent magnets due to there is no collector and brush. So, there is no maintenance, no arc and reduced friction loss. The poles number in the rotor can vary between 2 and 8 pole pairs with alternate south and north poles depending on the requirement of application. Permanent magnets are mounted on rotor with different forms. Generally, the magnets can be placed on the surface of the rotor. So as to reach maximum motor torque, the high flux density material should be used. The magnetic material on the rotor is needed to generate magnetic field density which is required.

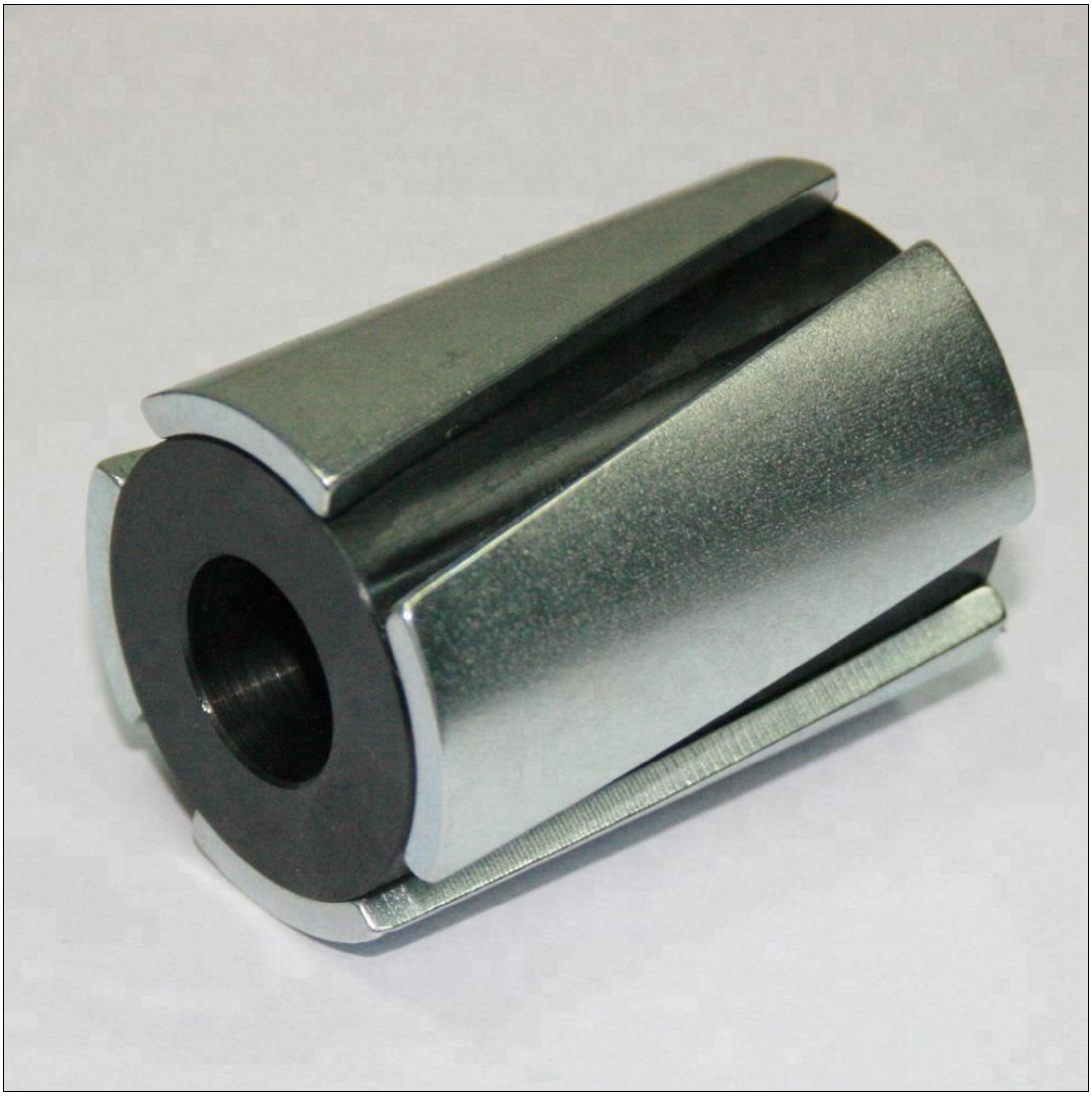

Figure 2.4 Rotor of the BLDC motor

Hall sensor provides the information for excitation stator of motor according to the rotor position. Because the BLDC motor is electronically controlled, the windings on the stator should be energized in specific sequence so as to rotate the motor. Before energizing a winding of stator, information of rotor position is necessary. So the Hall Effect sensor placed on stator in order to sense the rotor position.

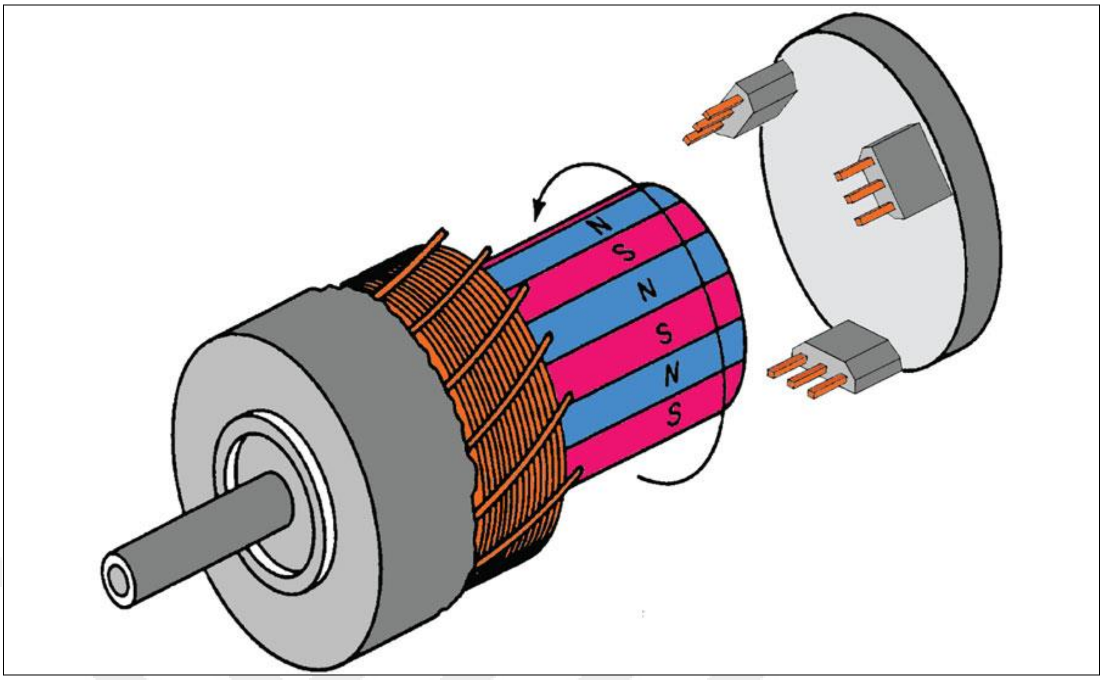

Figure 2.5 Hall sensors on the BLDC motor

2.2 Working Principle of BLDC Motor

Stator windings of a BLDC motor are connected to a control circuit which includes mosfets, gate driver integrated circuits etc. This control circuit energizes correct windings at correct time in order to rotate the rotor of the motor. The magnets of rotor try to align with the energized windings of the stator and as soon as alignment is completed. Then the next windings of the stator are energized. By this way the rotor keeps running.

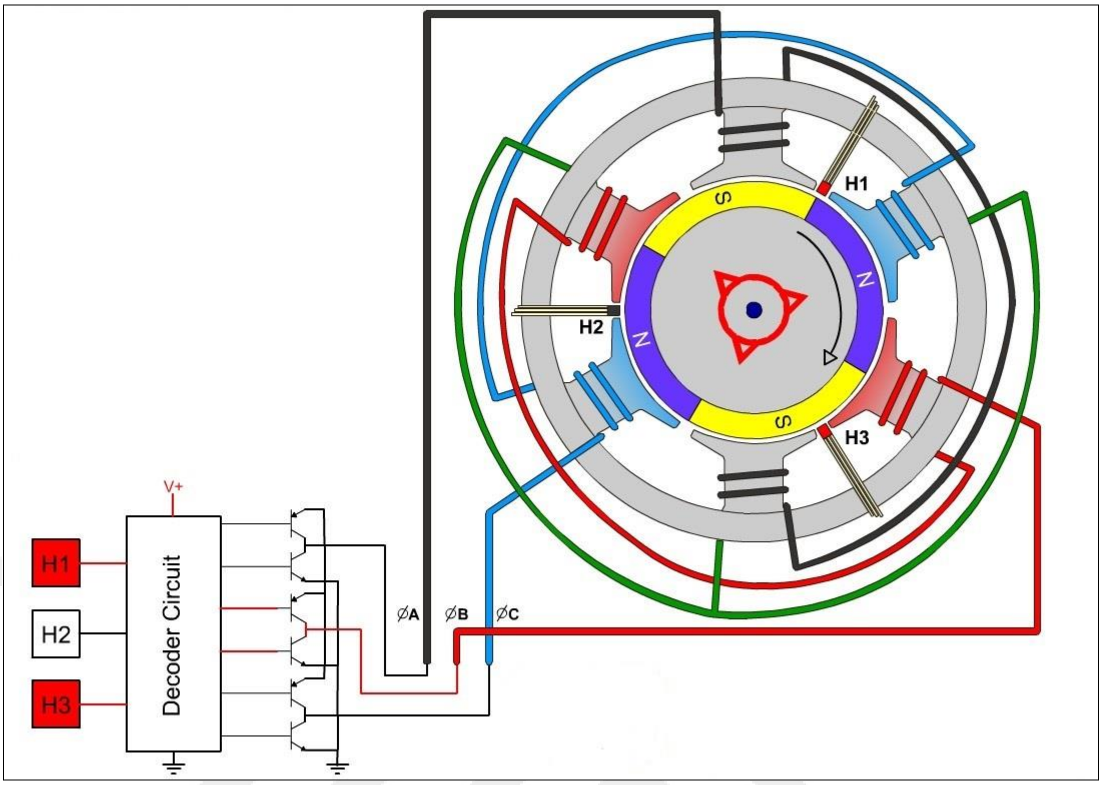

Figure 2.6 Connection of BLDC motor

2.3 BLDC Motors on the Missiles

BLDC motors are very important for missiles and defense industry. The BLDC motors are generally used in two important parts of guided missiles because of their high performance. One of these parts is gimbals and other is the fins.

Most of the missiles include gimbals. These gimbals usually include two BLDC motors and seeker camera. These motors provide two axis seeker camera motions, so the missiles can trace the target.

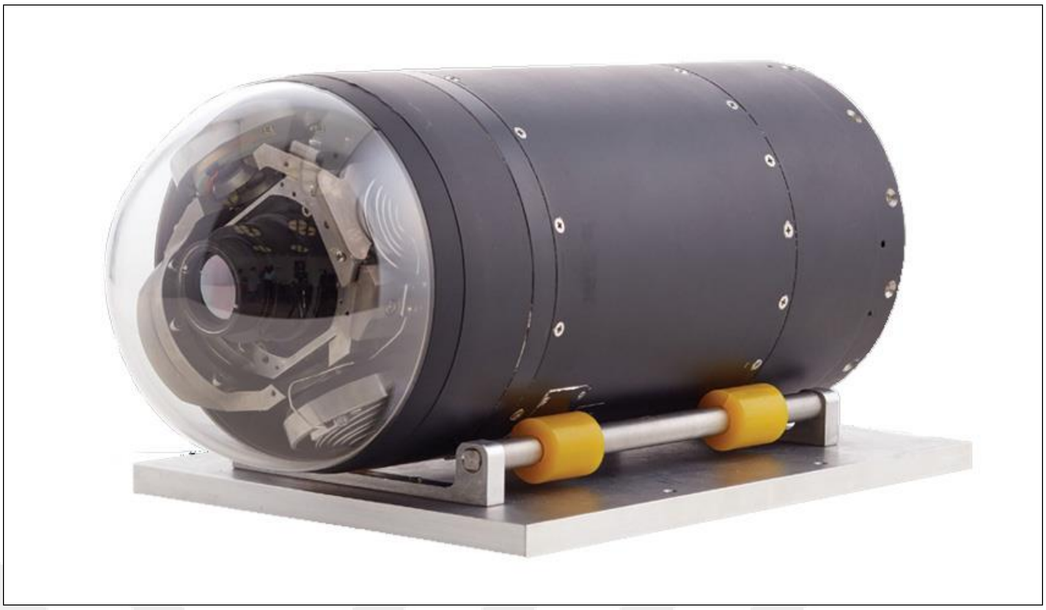

Figure 2.7 Gimbal of missile

Missiles generally have 4 fins and they can be guided to intended direction by BLDC motors that are used in the control system of fins.

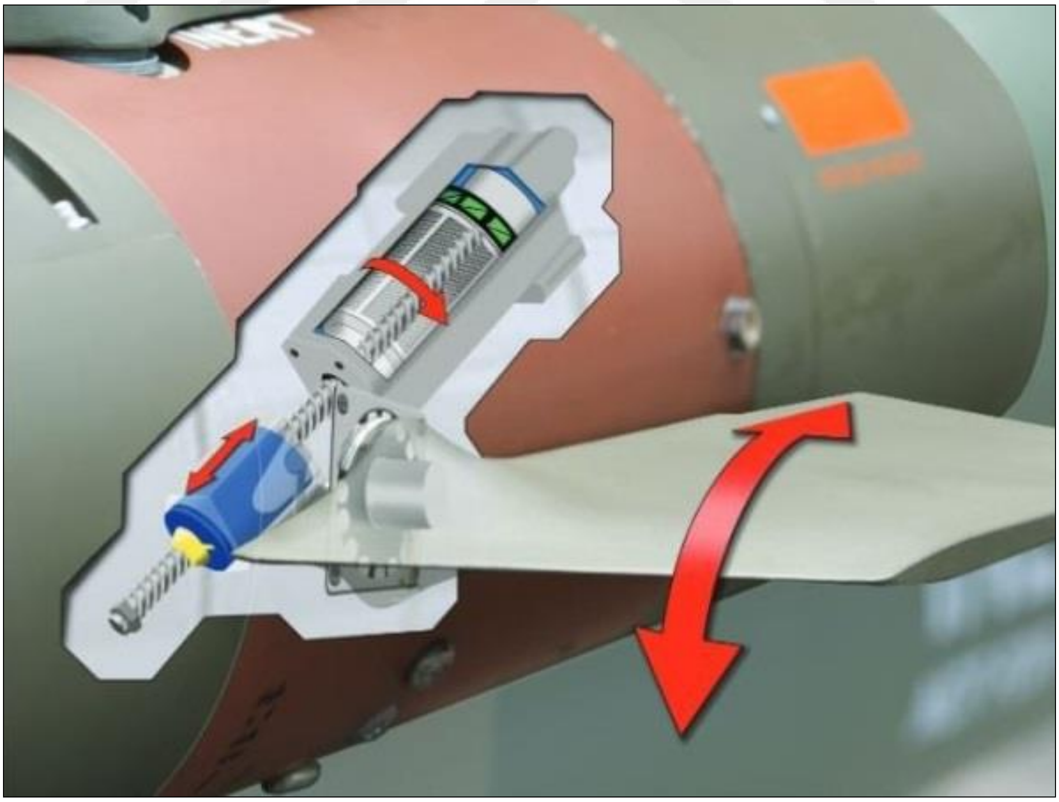

Figure 2.8 Fin of the missile

CHAPTER 3

CONTROL METHODS FOR BLDC MOTOR

There are lots of control methods for BLDC motor control. In this study, two methods of them are investigated; PI control method and Incremental Fuzzy control method. These methods were implemented separately as a motor current controller.

3.1 PI Control Method

In process control, a large part of the control methods are PI controller. PI controllers are nowadays preferred in all control processes. The controller methods come in a lot of varied configurations. PI control is usually combined with basic function blocks, consecutive functions, logic and selectors to set up complex systems that are often used for production, power generation and transport [4]. Also PI controller method is the most preferred method in the current control of motors [2]. Although many control methods are improved during several decades, PI control widely use in control systems.

The design and analyze of PI controller necessitate knowing these parameters, integral gain (- Ü; and proportional gain :- ã ; [4].

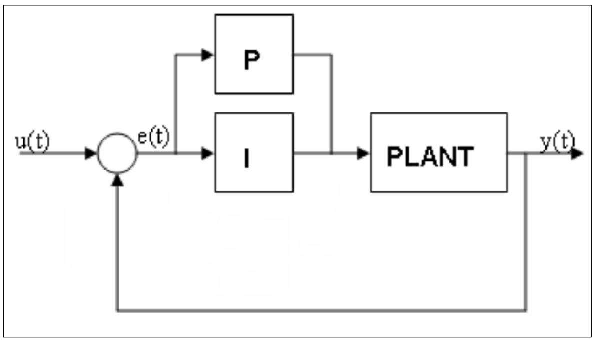

Figure 3.1 PI control method block diagram

PI controller formula is indicated in the below equation [2].

$$u(t) = K_i \int_0^t e(t)\,dt + K_p \, e(t) \qquad (3.1)$$

K_i: Integral gain, K_p: Proportional gain, $e(t)$: Error, t: Time, $u(t)$: Input

3.2 Incremental Fuzzy Control Method

PI controllers are used for several industrial control processes in view of their basic structure and wide range of operating conditions [15]. Its steady state and transient response performance in time invariant systems that the parameters, K_p and K_i are always constant during the process. While dynamics variations or environmental conditions are occurred, the PI controller is inefficient and unstable, because of the constant controller parameters give uncertain behavior. Instead of this method, fuzzy tuning control method is used for dynamic variations [16]. Fuzzy logic has been recognised to be very convenient in the designing of control systems [17]. Fuzzy logic control technique has been successfully applied in many consumer products and engineering areas since 1974 [18].

$$P = P + FIS(e(t), \dot{e}(t)) \times K_{p} \qquad (3.2)$$

$$I = I + FIS(e(t), \dot{e}(t)) \times K_{i} \qquad (3.3)$$

$FIS(e(t), \dot{e}(t))$ is output of fuzzy inference system.

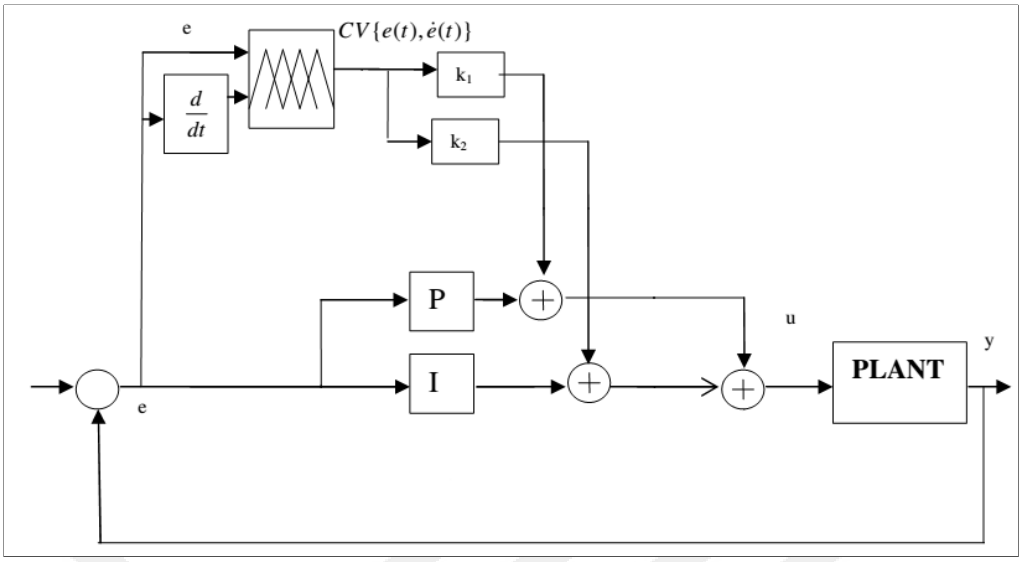

Figure 3.2 Incremental Fuzzy control method block diagram

In fuzzy control, the input of the system should be converted into the corresponding fuzzy representations [20]. There are two input of Incremental Fuzzy control method; error and change of error. All errors and change of errors have different fuzzy representation according to their numeric value.

Table 3.1 Classification of error and change of error

Error or Change of Error	**LP**	Large Positive	E > 200 mA
	SP	Small Positive	50 < E < 200 mA
	Z	Zero	-50 < E < 50 mA
	SN	Small Negative	-200 < E < -50 mA
	LN	Large Negative	E < -200 mA

Incremental Fuzzy control is Rule-Based method. In this method output of Fuzzy is defined according to two inputs. These inputs are; Error and Change of Error. Relationship between output and inputs is basically If-Then format. For example:

- If error is large negative and change of error is large negative then output is small positive,

- If error is small negative and change of error is large negative then output is big positive,
- If error is small negative and change of error is small negative then output is small negative,

…

Fuzzy Rule table is completed when output is defined for all condition of error and change of error. So the fuzzy outputs are provided by a fuzzy model, which is set of fuzzy logic rules [20].

Table 3.2 Fuzzy rule table

		Š ‹ š				
		LN	SN	Z	SP	LP
	LN	SP	BN	VBN	VBN	VBN
	SN	BP	SN	MN	MN	VBN
e	Z	BP	MP	Z	MN	BN
	SP	VBP	MP	MP	SP	MN
	LP	VBP	VBP	VBP	BP	SP

Fuzzy output is generated according to Fuzzy Rule Table by using classes of error and change of error. The fuzzy output can be converted back into their relevant numerical outputs [20]. These output values represent the degree of Fuzzy tuning effect on PI control method.

Table 3.3 Numeric value of fuzzy output

Fuzzy Out	**VBP**	Very Big Positive	8
	BP	Big Positive	6
	MP	Medium Positive	4
	SP	Small Positive	2
	Z	Zero	0
	SN	Small Negative	-2
	MN	Medium Negative	-4
	BN	Big Negative	-6
	VBN	Very Big Negative	-8

Effects of Fuzzy output are different for PI parameters. Degree of effect on - ã parameter depends on - ã 4¿ gain. - Ü4¿ gain sets the effect of Fuzzy output on the - Ü parameter. These parameters were determined by using heuristic approach.

Table 3.4 PI and fuzzy gain parameters

w_	50
w•	6
w_4r	100
w•4r	30

CHAPTER 4

CIRCUIT DESCRIPTION AND OPERATION

Controlling of motor which is used on missiles is not easy process. A complex electronic board which can operate many of process simultaneously is needed. The electronic board which is used to control motor includes six main circuit modules. All of these modules are related with each other. Also this electronic board must work properly under the tough environmental conditions such as excessive vibration, high acceleration, over speed, cold and hot weather condition etc.

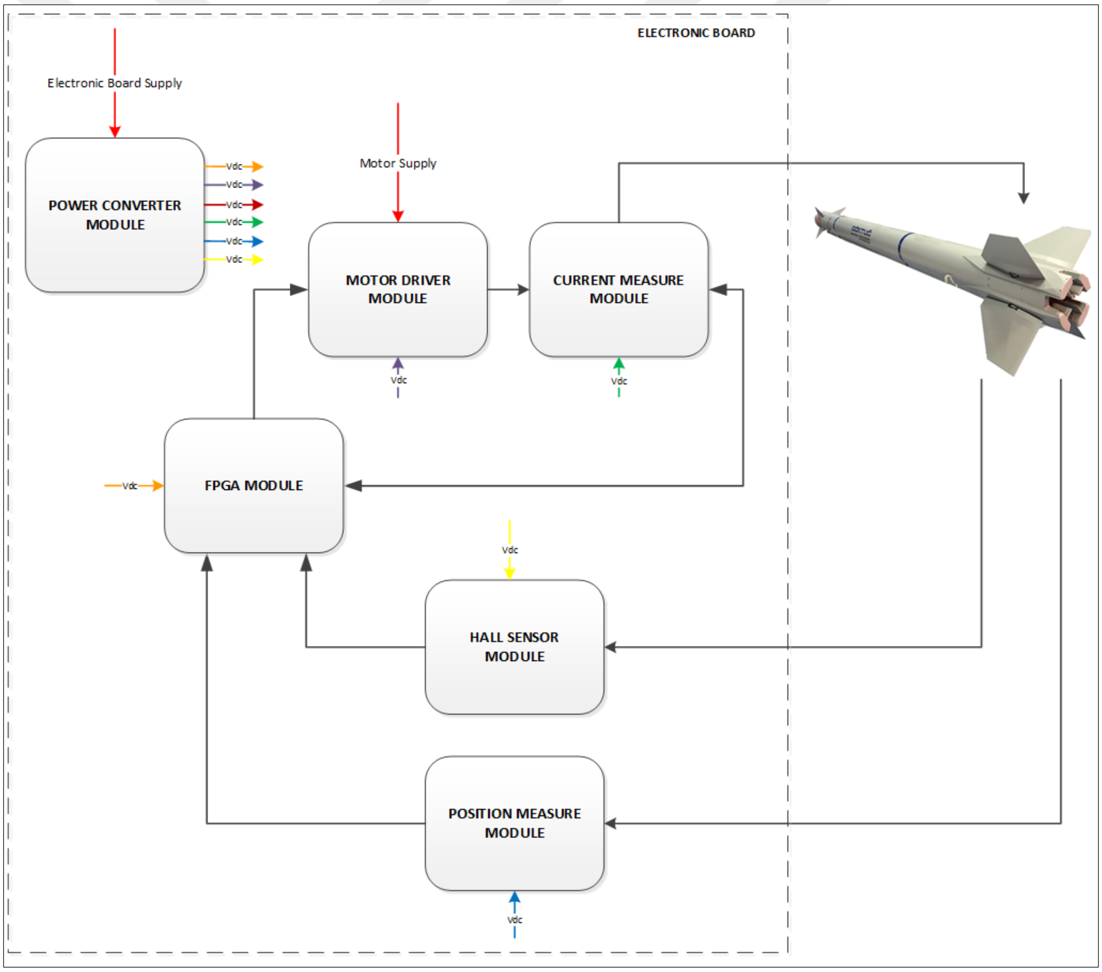

Figure 4.1 Block diagram of electronic board

4.1 Power Converter Module

28V is required to work properly all functions of electronic board. All required voltages for ADCs, FPGA, current sensors, buffers, gate drivers, hall sensors and encoders are generated by using 28V input voltage of electronic board. And these generated voltages deliver to the components.

4.2 Position Measure Module

Two digital data signals Data A and Data B come to electronic board from incremental encoder. Data A and Data B digital data signals are read by using buffers and FPGA. Buffers strengthen data signals and regulate voltage levels to become suitable for FPGA. FPGA increases or decreases the value of position register according to Data A and Data B pulses. So the motor's position data can be stored on this position register.

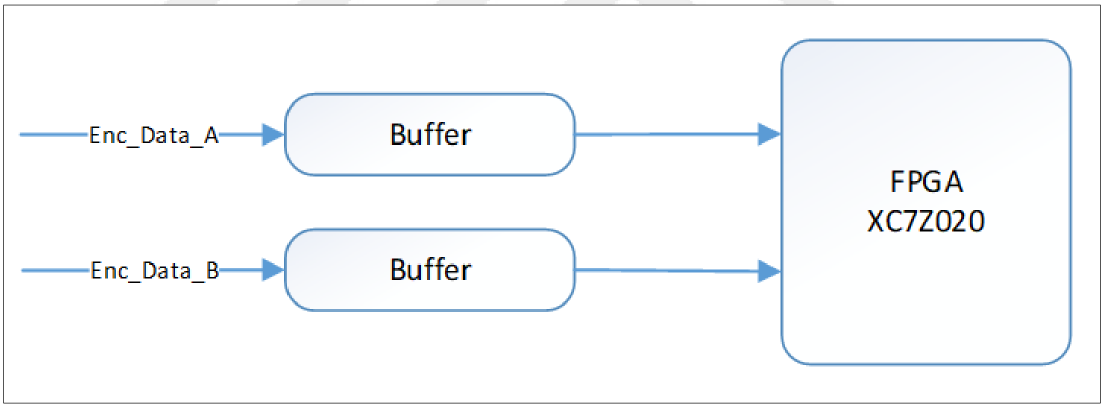

Figure 4.2 Position read structure

4.3 Hall Sensor Module

Three digital data signals Hall 1, Hall 2 and Hall 3 come to electronic board from hall sensor. These digital data signals are read by using comparator IC and FPGA. Comparator IC compares the 15V hall signals with 5V. If voltage levels of hall signals are over the 5V then comparator generate 3.3V output signals. Otherwise the voltage levels of hall signals are under the 5V then comparator generate 0V output.

FPGA determines which mosfets will be activated according to these hall sensor signals.

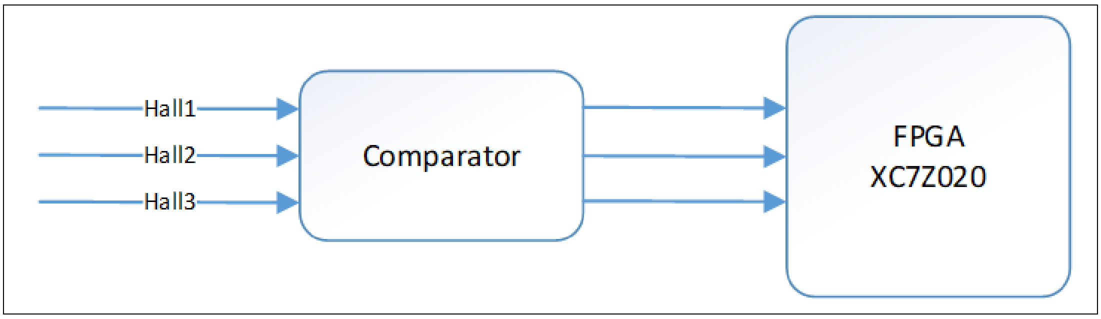

Figure 4.3 Hall sensor read structure

4.4 Current Measure Module

The current that flow on phases of motor go through also current sensor (ACS709LLFTR). Thus the phase's current can be measured. These current feedbacks use as an input of motor control module. Current sensor gives an analog voltage feedback according to current. And this analog feedback is converted to digital signal by using 2 MSPS ADC (AD7944BCPZ). This converted digital data is read by FPGA with SPI interface.

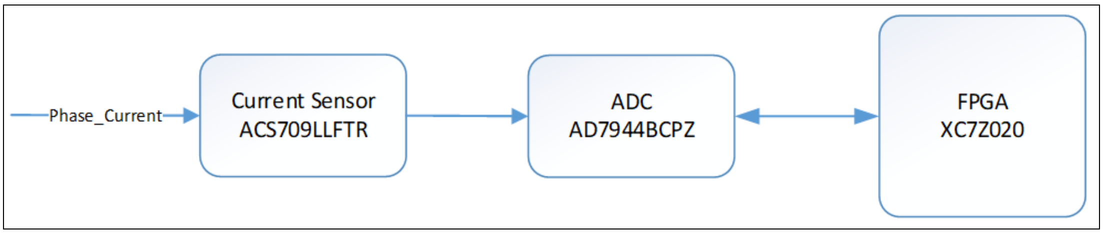

Figure 4.4 Phase current read structure

4.5 Motor Driver Module

This module includes gate drivers (FAN7391MX), mosfets (IRFSL4127PBF) and other electronic component such as resistors, diodes, capacitors. FPGA sends switching signals with 20 kHz frequency to gate drivers and according to these trigger signals, gate drivers close or open the mosfets. So current can flow through a phase of motor and can come back another phase of motor.

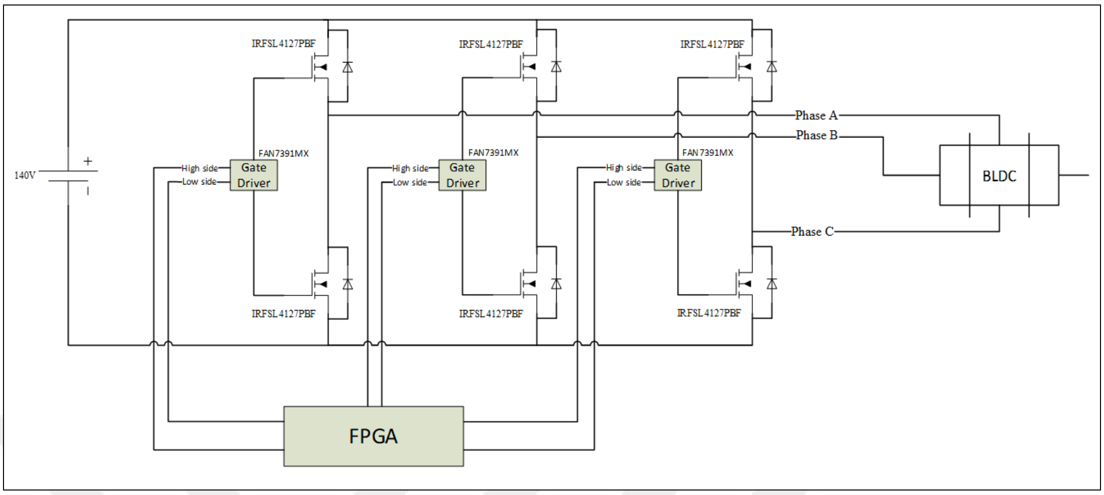

Figure 4.5 Structure of motor driver circuit

FPGA drives the gate driver integrated circuits according to the six step commutation technique. In this technique, FPGA reads six different hall sensor data combinations which come from motor and activates two mosfets of driver circuit. One of these mosfets is high side mosfet of one phase. And the other mosfet is low side mosfet of another phase. So current goes through on one phase and comes back on another phase.

Table 4.1 Motor commutation table

Hall Sensor Signals			Gate Driver Signals					
H1	**H2**	**H3**	**A_H**	**A_L**	**B_H**	**B_L**	**C_H**	**C_L**
1	0	0	1	0	0	1	0	0
1	1	0	1	0	0	0	0	1
0	1	0	0	0	1	0	0	1
0	1	1	0	1	1	0	0	0
0	0	1	0	1	0	0	1	0
1	0	1	0	0	0	1	1	0

When Hall 1, Hall 2 and Hall 3 signals are 1, 0, 0 respectively, FPGA drives the high side of the phase A gate driver and low side of the phase B gate driver. Then phase A high side mosfet and phase B low side mosfet are activated. So the current goes to motor over the phase A and comes back from motor over the phase B.

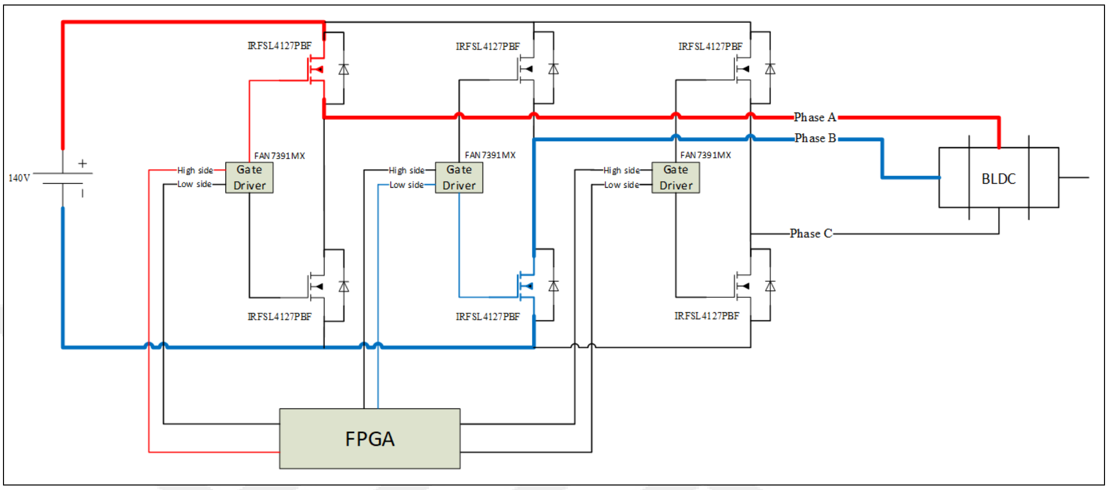

Figure 4.6 Phase A high side mosfet and phase B low side mosfet active state

When Hall 1, Hall 2 and Hall 3 signals are 1, 1, 0 respectively, FPGA drives the high side of the phase A gate driver and low side of the phase C gate driver. Then phase A high side mosfet and phase C low side mosfet are activated. So the current goes to motor over the phase A and comes back from motor over the phase C.

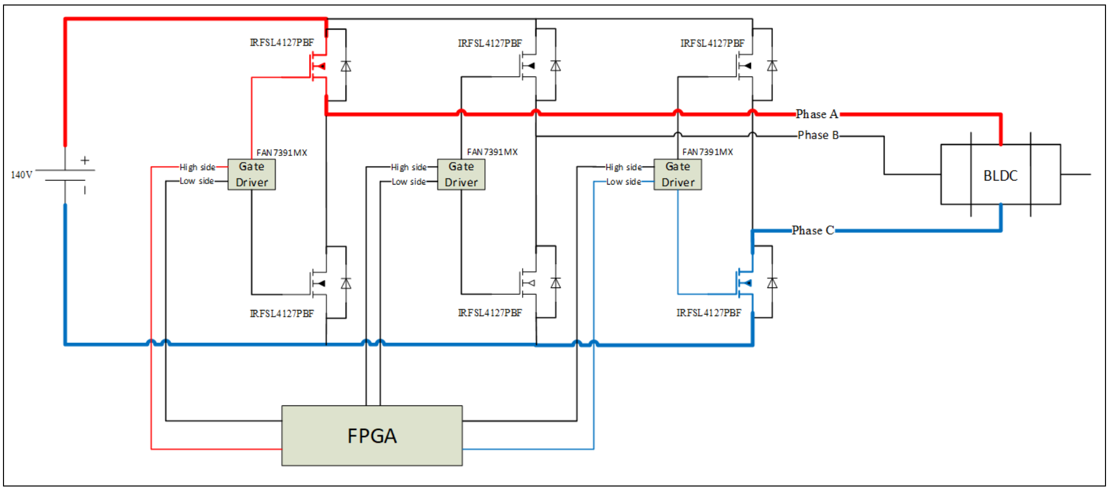

Figure 4.7 Phase A high side mosfet and phase C low side mosfet active state

When Hall 1, Hall 2 and Hall 3 signals are 0, 1, 0 respectively, FPGA drives the high side of the phase B gate driver and low side of the phase C gate driver. Then phase B high side mosfet and phase C low side mosfet are activated. So the current goes to motor over the phase B and comes back from motor over the phase C.

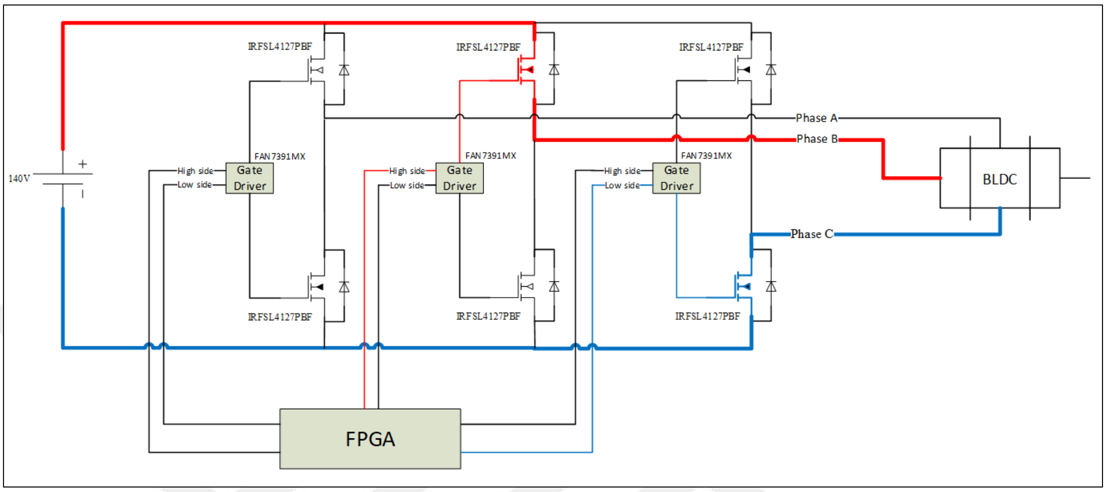

Figure 4.8 Phase B high side mosfet and phase C low side mosfet active state

When Hall 1, Hall 2 and Hall 3 signals are 0, 1, 1 respectively, FPGA drives the high side of the phase B gate driver and low side of the phase A gate driver. Then phase B high side mosfet and phase A low side mosfet are activated. So the current goes to motor over the phase B and comes back from motor over the phase A.

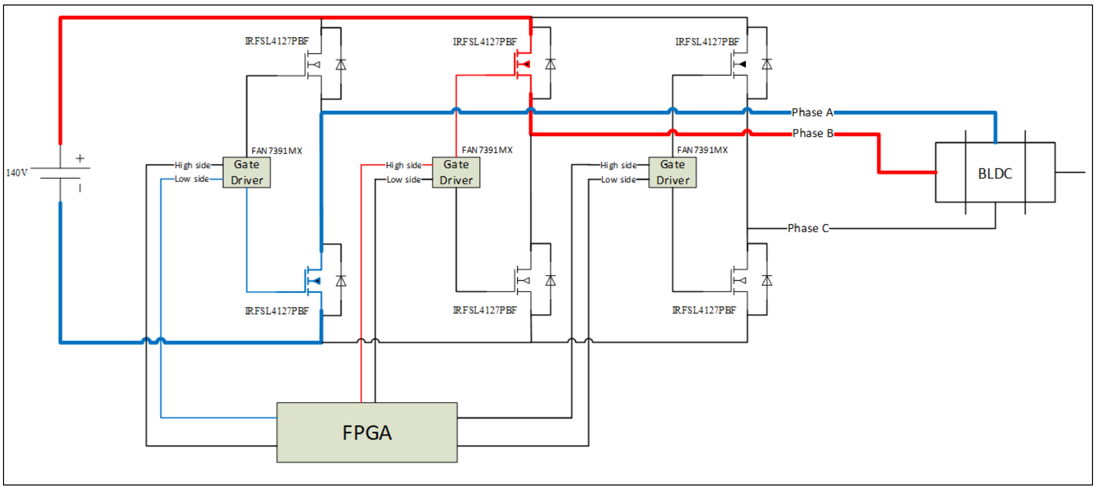

Figure 4.9 Phase B high side mosfet and phase A low side mosfet active state

When Hall 1, Hall 2 and Hall 3 signals are 0, 0, 1 respectively, FPGA drives the high side of the phase C gate driver and low side of the phase A gate driver. Then phase C high side mosfet and phase A low side mosfet are activated. So the current goes to motor over the phase C and comes back from motor over the phase A.

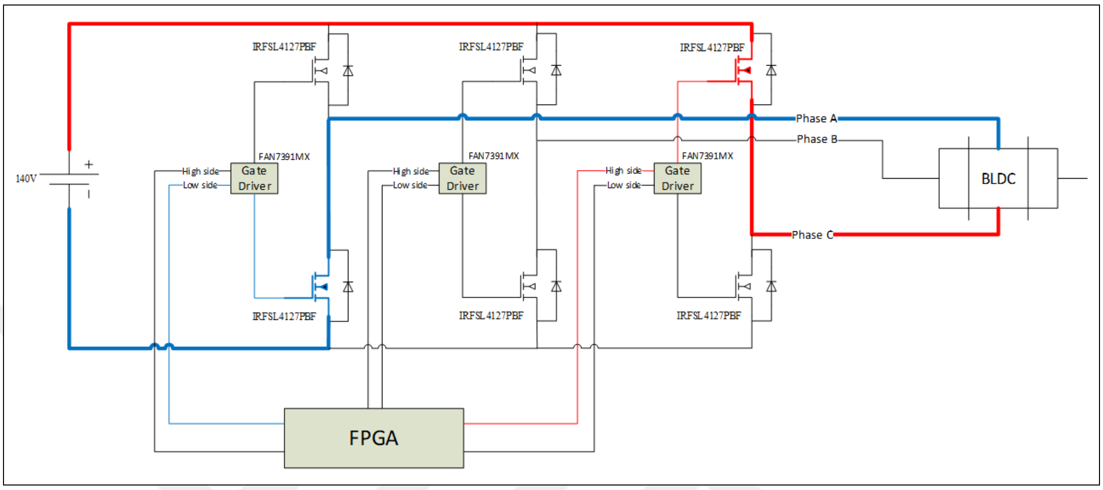

Figure 4.10 Phase C high side mosfet and phase A low side mosfet active state

When Hall 1, Hall 2 and Hall 3 signals are 1, 0, 1 respectively, FPGA drives the high side of the phase C gate driver and low side of the phase B gate driver. Then phase C high side mosfet and phase B low side mosfet are activated. So the current goes to motor over the phase C and comes back from motor over the phase B.

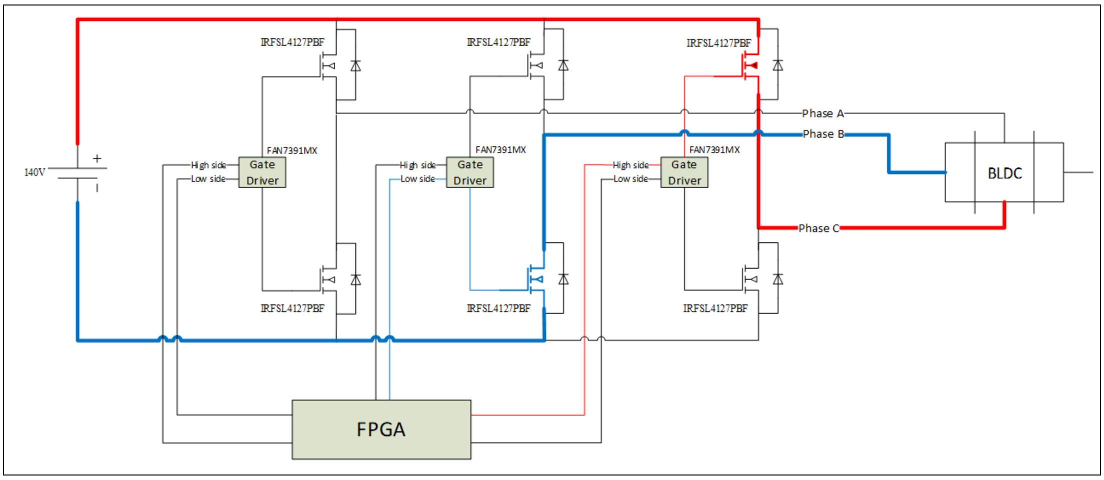

Figure 4.11 Phase C high side mosfet and phase B low side mosfet active state

4.6 FPGA Module

FPGA (XC7Z020) manages other modules. Current and position feedbacks are read with the help of FPGA. Current control algorithms are implemented on FPGA. Position control algorithm is implemented on microprocessor. FPGA and microprocessor are integrated on the same chip.

FPGA module includes more than one sub modules which can be shown on Figure 4.14. Most important of them is Controller Module. We implemented Incremental Fuzzy control method and PI control method on Controller Module. Processes of PI and Incremental Fuzzy method are shown on Figure 4.12 and Figure 4.13 respectively.

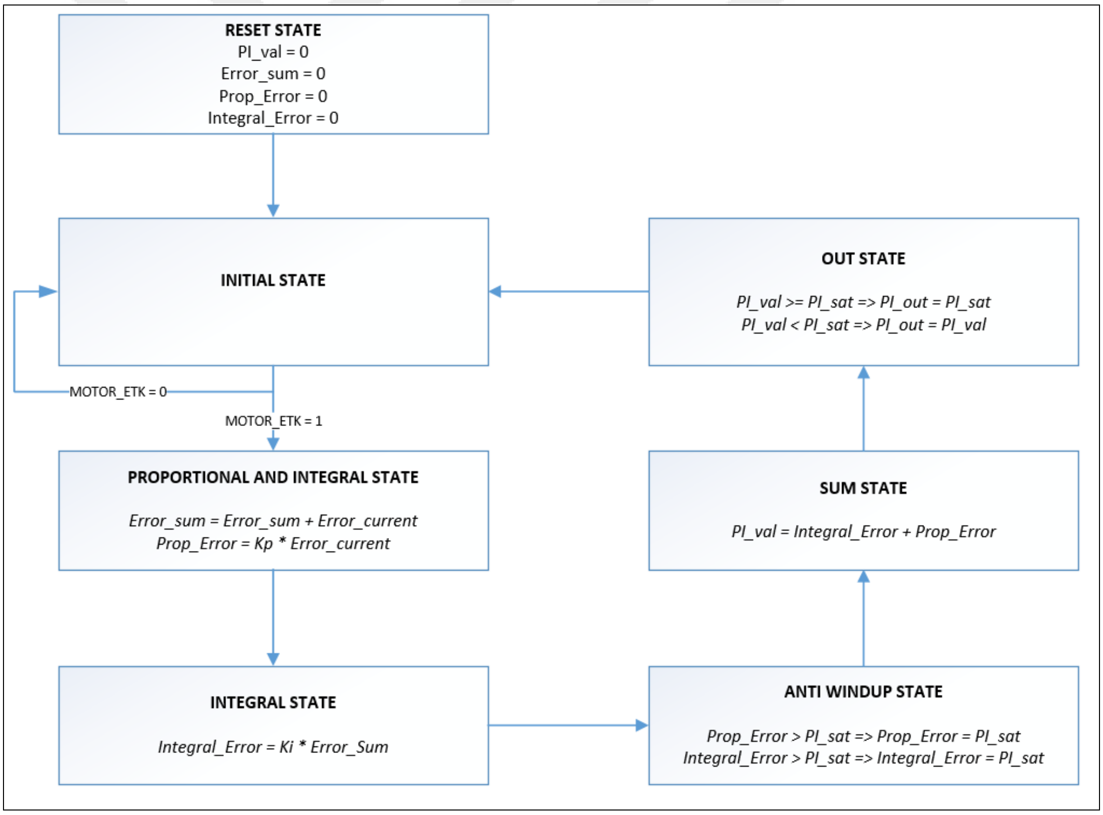

Figure 4.12 PI control method state diagram

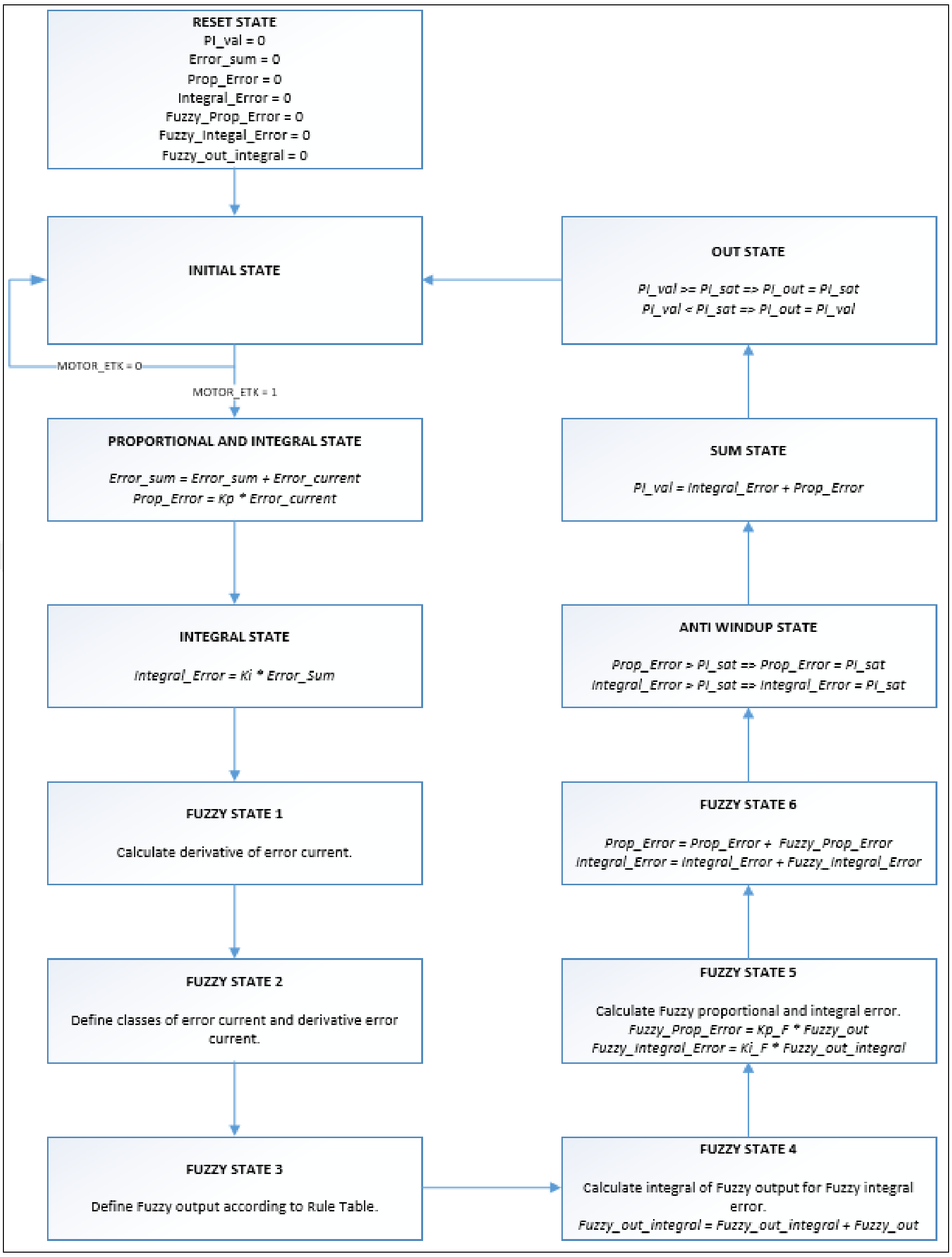

Figure 4.13 Incremental Fuzzy control method state diagram

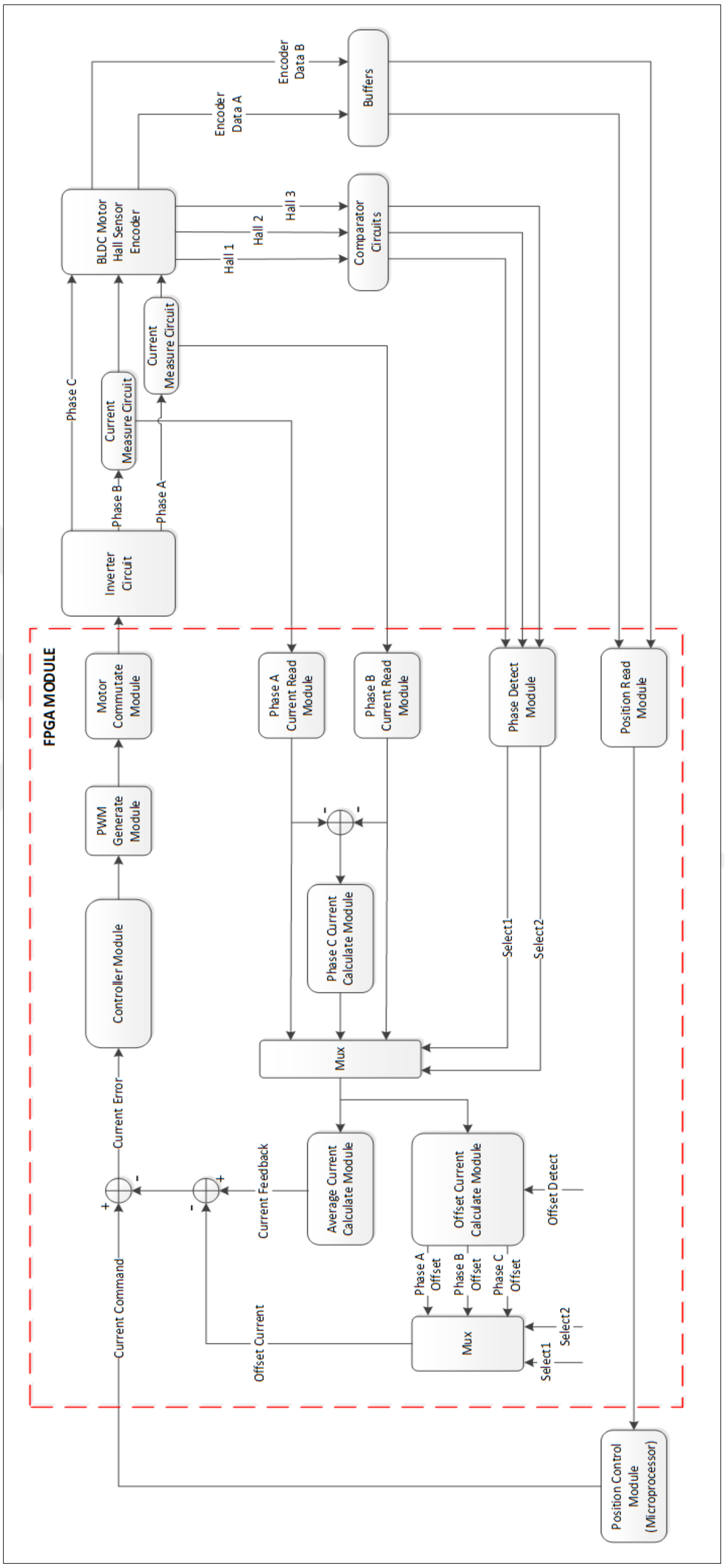

Figure 4.14 Detailed FPGA module and connection with other components

CHAPTER 5

SIMULATION STUDIES

Simulation results for PI and Incremental Fuzzy control methods were obtained by using Matlab Simulink. Some parameters which were used for designing simulation circuits are shown on Table 5.1.

Table 5.1 Some parameters for Matlab design

PARAMETER	VALUE
Motor Bus Voltage	140 V
Switching Frequency	20 kHz
Mosfet Resistance Ron	0.02 ohm
Internal Diode Resistance Rd	0.01 ohm
Internal Diode Forward Voltage Vf	1.3 V
Snubber Resistance Rs	1e5 ohm
Stator Phase Resistance	1.9 ohm
Stator Phase Inductance	0.0014 H

5.1 PI Control Method Simulation

Below circuit was designed on Matlab Simulink to simulate performance of PI controller. On this design, begin with position command is given to system as an input. Secondly, speed command is generated by using calculated position error. After that current command is generated by using calculated speed error. Then current error is calculated from current command and current feedback and this error is used as an input to PI controller. Output of PI controller is used in PWM generator block. According to PWM signal and hall sensor data, gates of mosfets are driven. By this way desired current flow over the opened mosfets. 140 V supply is used as a bus voltage.

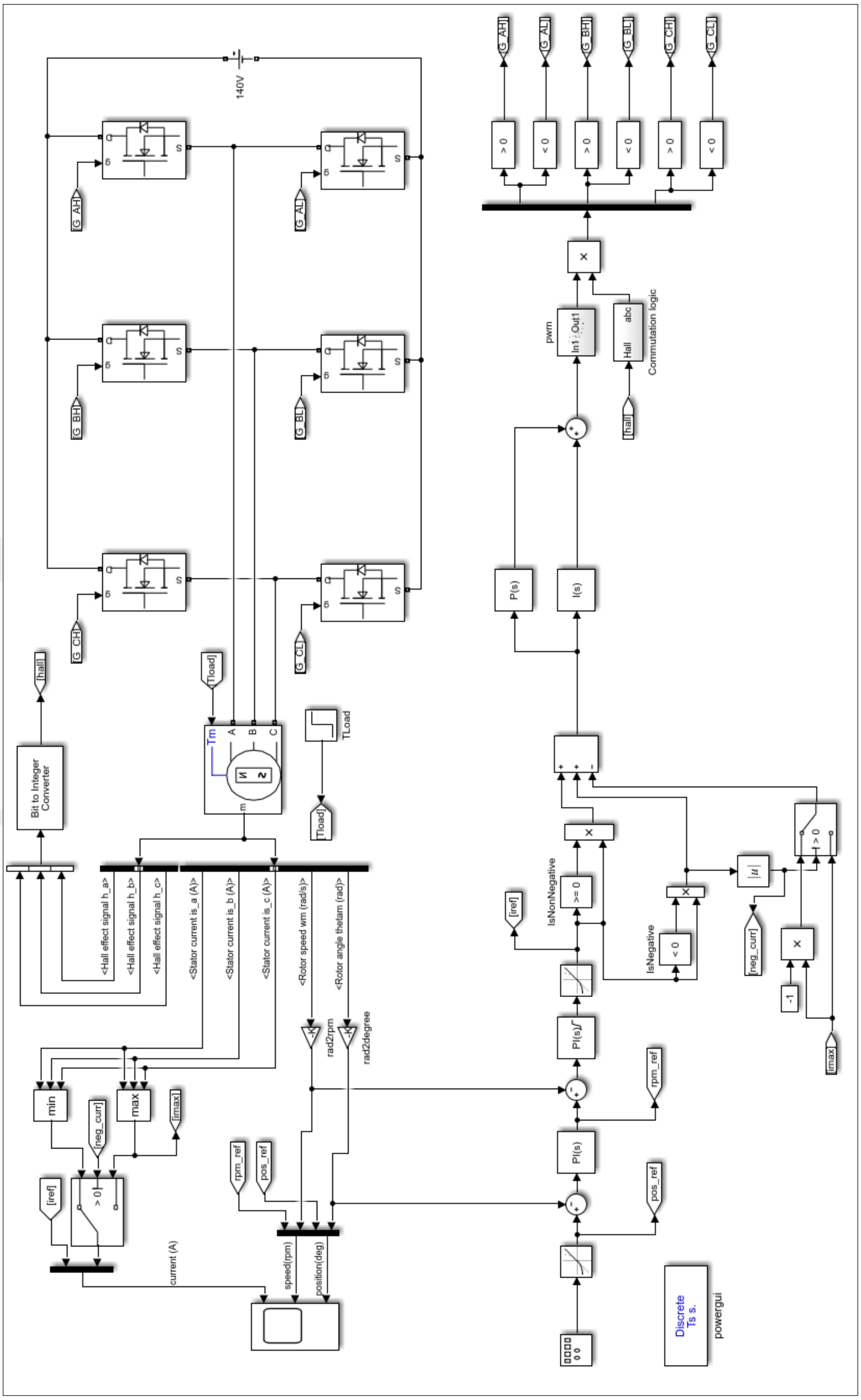

Figure 5.1 Matlab design of PI control

Figure 5.2 show us command vs feedback graphics for position, speed and current on PI controller. Feedback data usually can trace command data. But rarely the feedback cannot trace the command and there are some unexpected feedbacks.

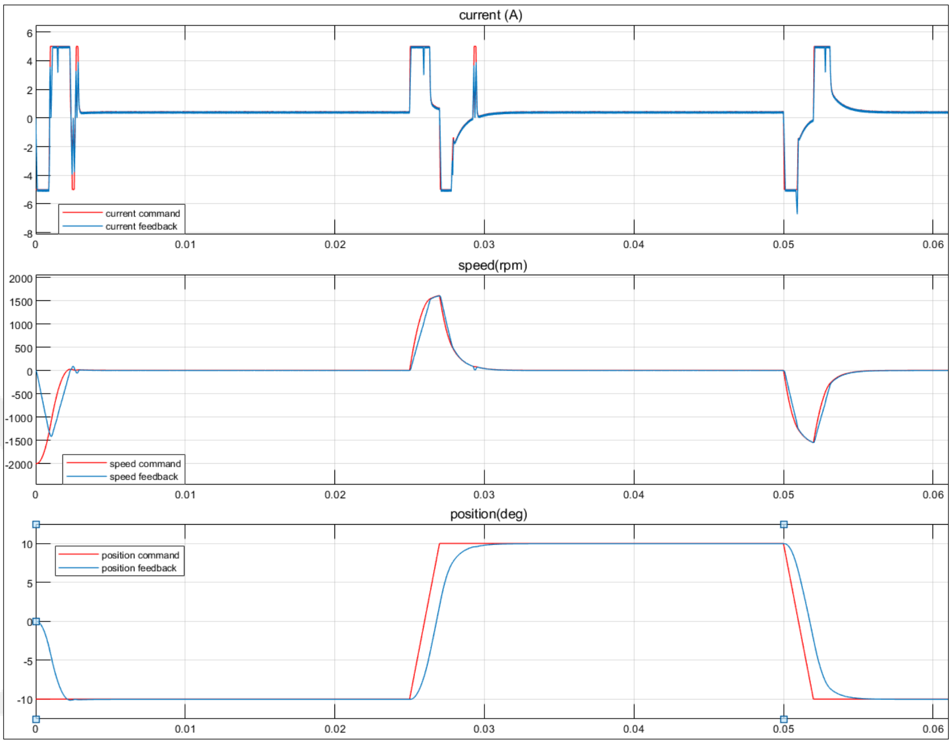

Figure 5.2 Simulation test results for PI control

5.2 Incremental Fuzzy Control Method Simulation

Below circuit was designed on Matlab Simulink to simulate performance of Incremental Fuzzy control method. On this design, controller is begun with position command is given to system as an input. Then, speed command is produced by using position error. After that current command is obtained by using speed error. Later, current error is calculated by using current feedback and current command and this current error is used as an input of Incremental Fuzzy control. Fuzzy process tunes the parameters of PI controller according to change of current error and current error. Output of this controller is used in PWM generator module. Finally gates of mosfets are driven according to PWM signal and hall sensor data. By this way expected current flow through the opened mosfets.

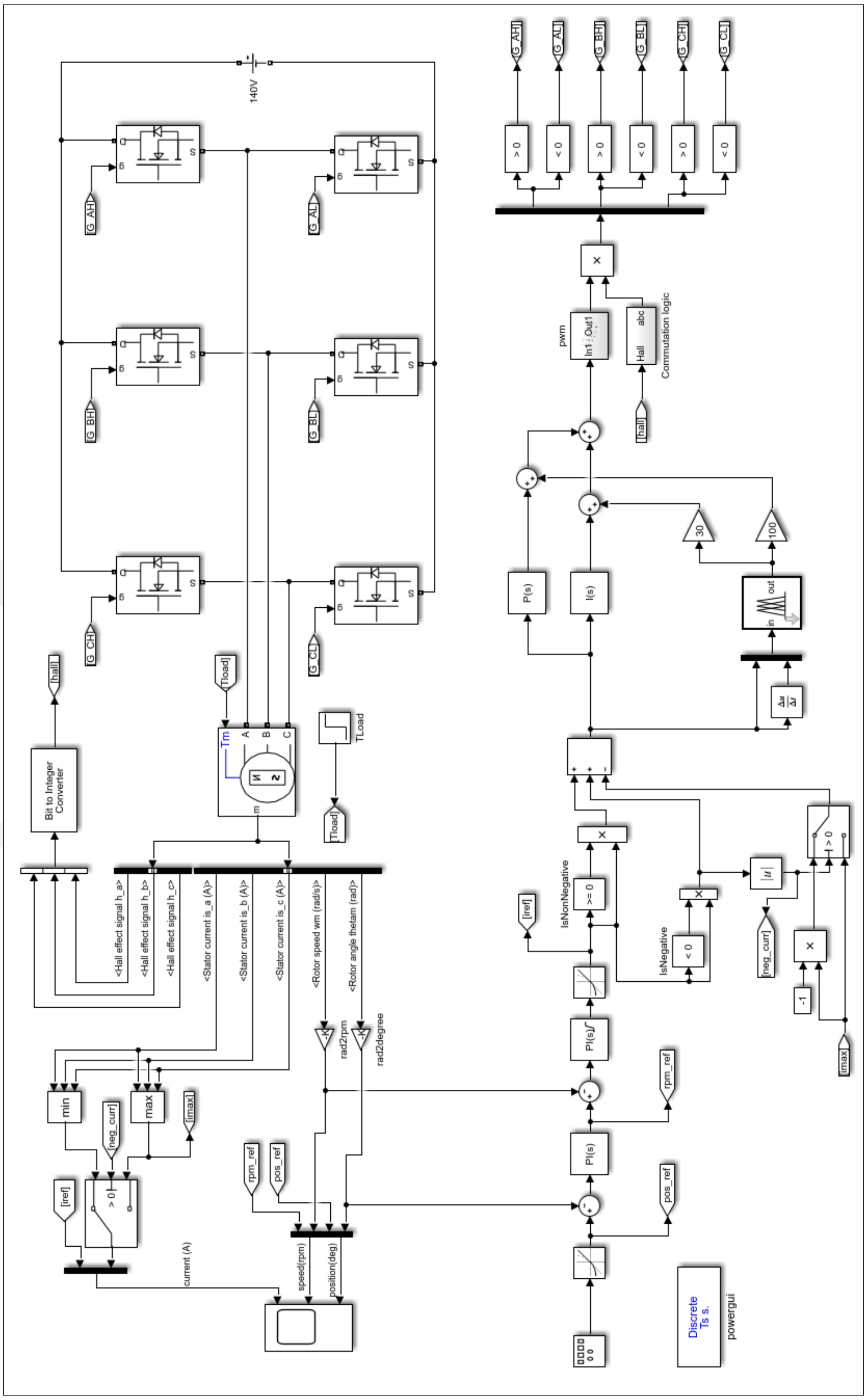

Figure 5.3 Matlab design of Incremental Fuzzy control

Figure 5.4 shows feedback vs command graphics for current, position and speed on Incremental Fuzzy control. Feedback data almost always can trace commands. Generally, controller is successful, stable and efficient.

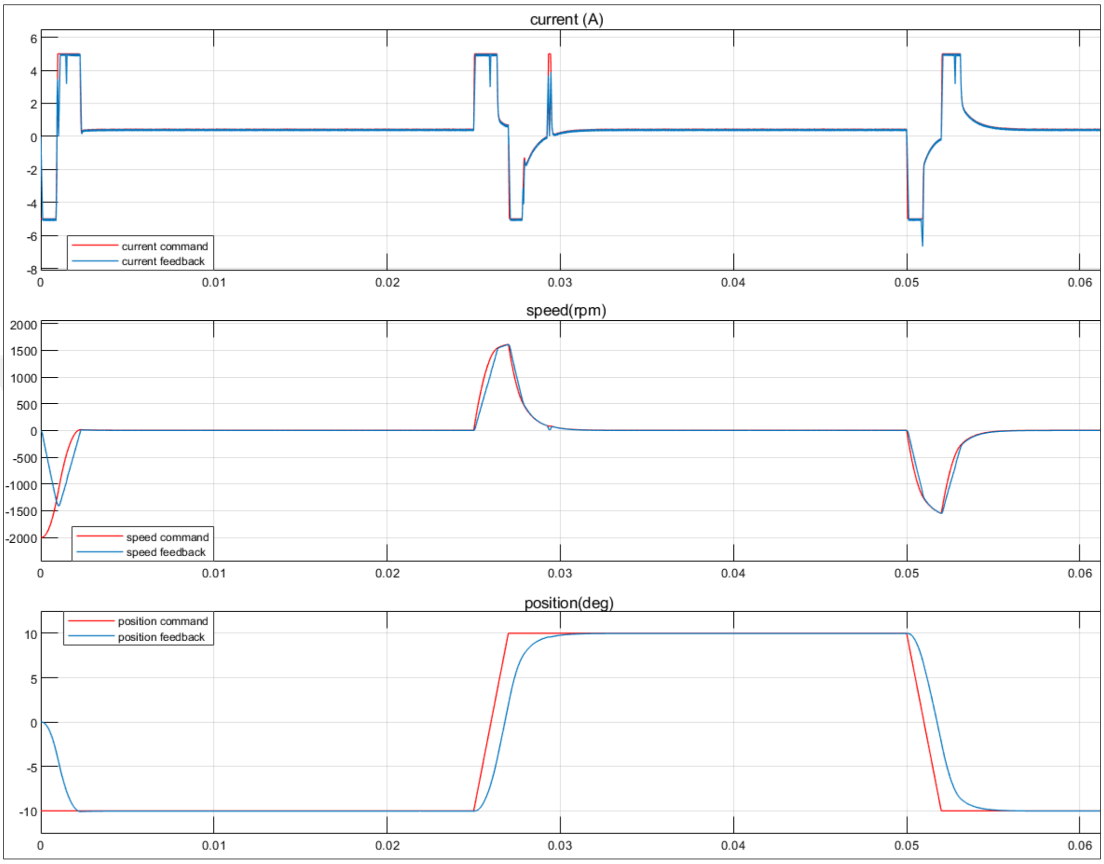

Figure 5.4 Simulation test results for Incremental Fuzzy control

5.3 PI vs Incremental Fuzzy Control

If we focus at between 0.002 – 0.003 seconds on PI and Incremental Fuzzy simulation result graphics, we can see easily unwanted oscillation on current, speed, position graphics of PI control. But there is any unexpected situation such as this oscillation on all graphics of Incremental Fuzzy control.

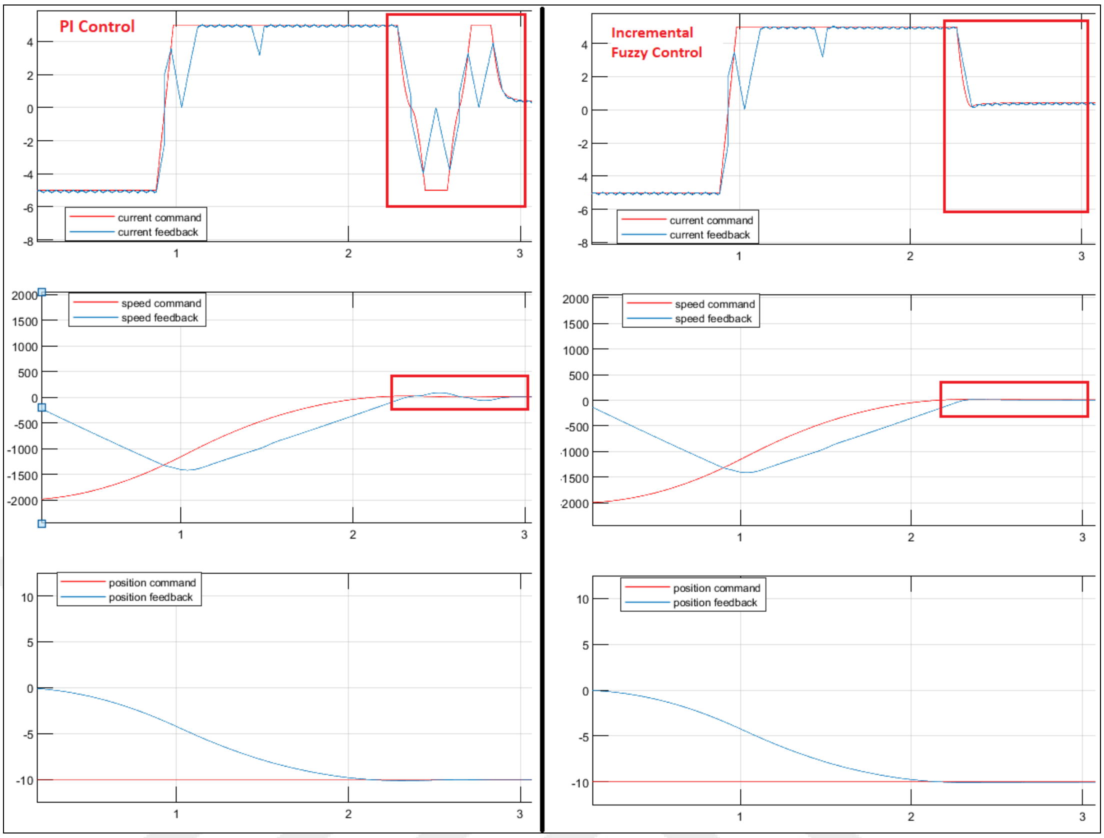

Figure 5.5 PI vs Incremental Fuzzy control

CHAPTER 6

EXPERIMENTAL STUDIES

Our experimental test setup is include PC, electronic board, cables for electronic board connection with PC and BLDC motor, BLDC motor and power supplies. PC (1) sends the position and current commands to electronic board (3). Also data which came from board are collected by using PC. One of the cables (2) provides the power transmission from power supplies to electronic board and the communication between electronic board and PC. Other cable (4) connects the motor (5) and electronic board to each other. One of the power supplies (6) gives to electronic board 140V to use as bus voltage. Other power supply (7) provides that electronic board work properly with 28V.

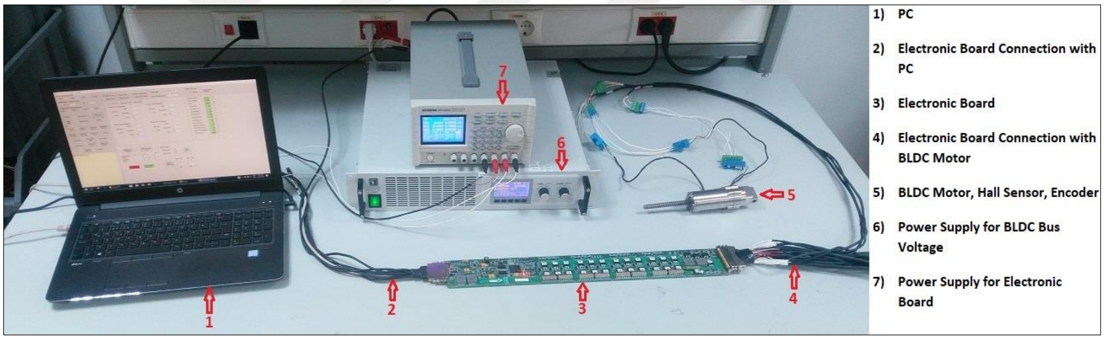

Figure 6.1 Experimental test setup

6.1 Experimental Tests for PI Control Method

6.1.1 Current Control Test

The first experimental test for PI Control Method was current control test. The applied command is 1000 mA, 100 Hz, square wave which is shown on Figure 6.2. BLDC motor always cannot track properly the current command with PI control. There are a lot of noises on steady state.

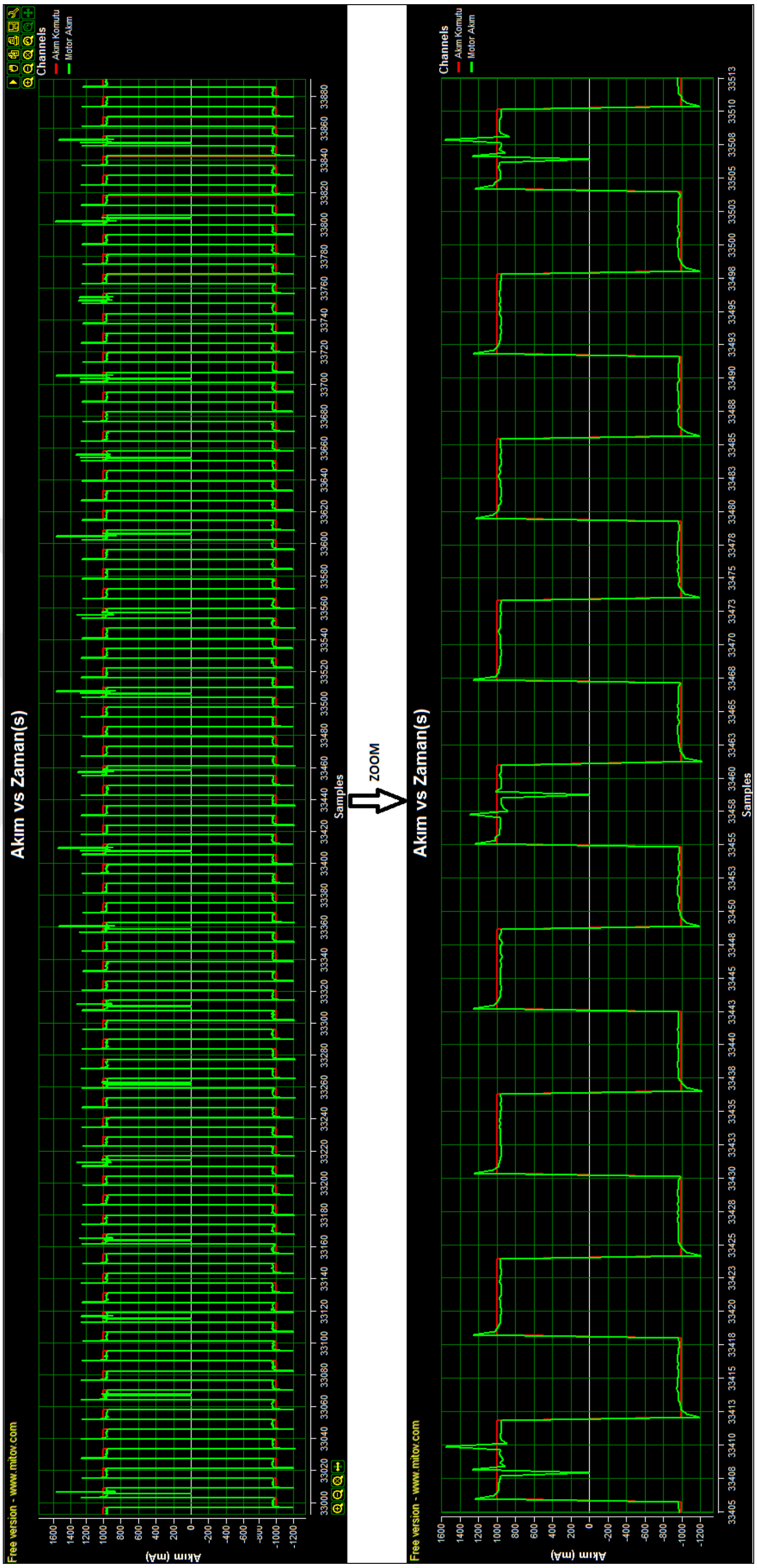

Figure 6.2 Experimental test results for PI control on current control test

Table 6.1 Data table of PI control for current control test

Time (ms)	Current Command (mA)	Current Feedback (mA)
33454.8200	-997.3839	-970.1330
33455.0600	997.3839	1242.6420
33455.3100	997.3839	1019.1850
33455.5500	997.3839	1013.7340
33455.8000	997.3839	970.1330
33456.0500	997.3839	975.5832
33456.3000	997.3839	964.6828
33456.5400	997.3839	959.2327
33457.0400	997.3839	964.6828
33457.2900	997.3839	1297.1440
33457.5300	997.3839	882.9301
33457.7800	997.3839	931.9817
33458.0200	997.3839	953.7825
33458.5200	997.3839	953.7825
33458.7700	997.3839	0.0000
33459.0100	997.3839	1013.7340
33459.2600	997.3839	964.6828
33459.7500	997.3839	964.6828
33460.0000	997.3839	948.3323
33460.7400	997.3839	953.7825
33460.9900	997.3839	964.6828
33461.2300	-997.3839	-1215.3910

Table 6.2 Some measurements of PI control for current control test

Measurement	Value
Rise time	~0.2 ms
Settling time	~2 ms
Overshoot	%25
Steady state error(positive command)	-%3
Steady state error(negative command)	-%3

6.1.2 Position Control Test

The next experimental test for PI Control Method was position control test. Two different position commands were applied two BLDC motor by using electronic board. One of these commands is 65 degree to -65 degree, 1 Hz, square wave position command which is shown on Figure 6.3. According to the position feedback data BLDC motor can trace this command with PI Control.

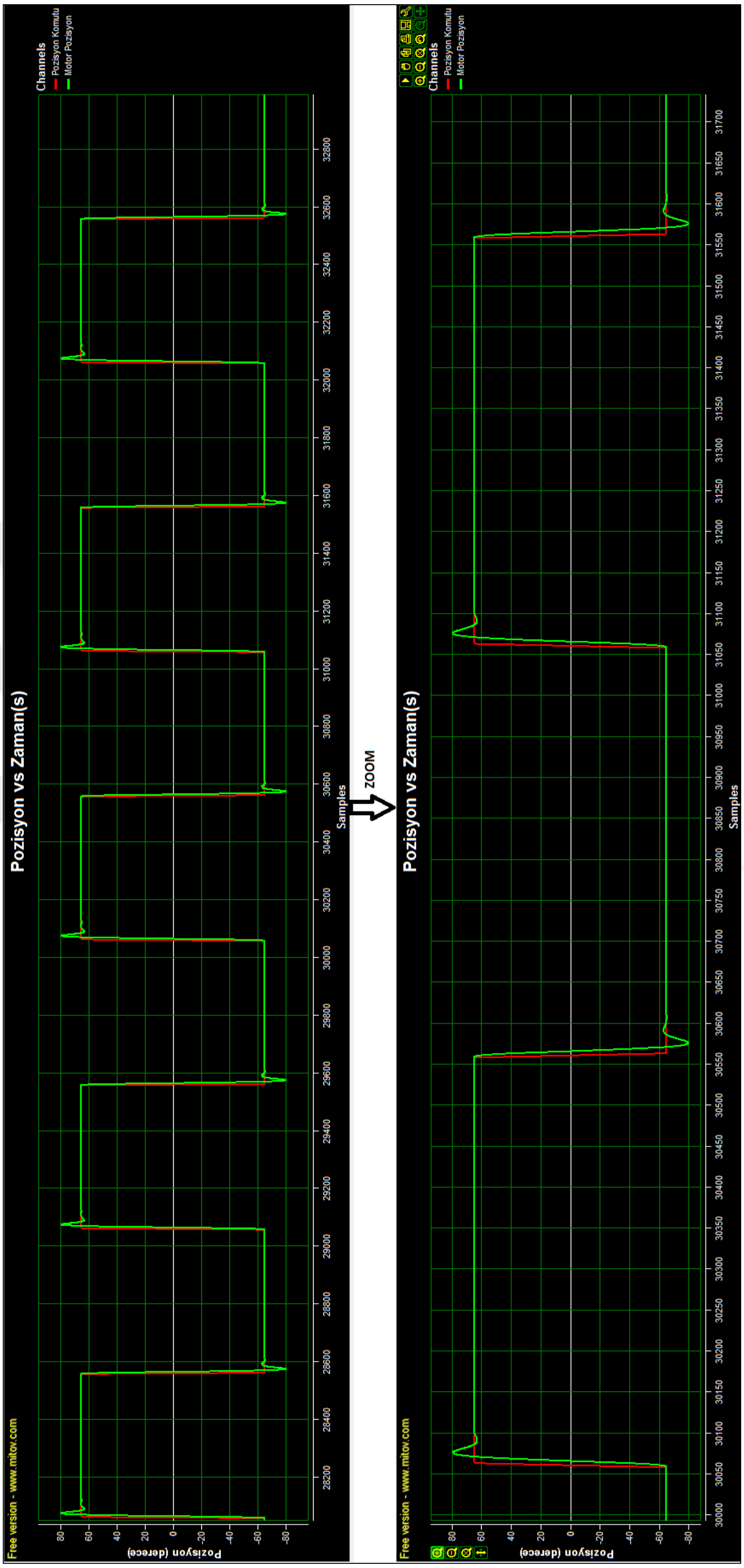

Figure 6.3 Experimental test results for PI control on position control test 1

Table 6.3 Data table of PI control for position control test 1

Time (ms)	Position Command (Angle)	Position Feedback (Angle)
30058.5200	-65.0000	-64.9480
30060.0000	-26.4810	-64.3370
30061.4800	12.0380	-58.8835
30062.9600	50.5570	-46.6700
30064.4500	65.0000	-27.4235
30065.9300	65.0000	-4.4850
30067.4100	65.0000	18.0180
30068.8900	65.0000	38.2330
30070.3700	65.0000	54.6650
30071.8500	65.0000	66.6185
30073.3300	65.0000	74.3535
30074.8100	65.0000	78.3120
30076.3000	65.0000	79.5405
30077.7800	65.0000	78.5720
30079.2600	65.0000	76.4660
30080.7400	65.0000	73.8270
30082.2200	65.0000	70.9280
30083.7000	65.0000	68.3800
30085.1900	65.0000	66.2675
30086.9100	65.0000	64.5125
30088.3900	65.0000	63.6350
30089.8800	65.0000	63.1085
30091.3600	65.0000	63.0175
30092.8400	65.0000	63.1930
30094.3200	65.0000	63.4595
30095.8000	65.0000	63.8105
30097.2800	65.0000	64.1615
30098.7700	65.0000	64.4215
30100.2500	65.0000	64.6880
30101.7300	65.0000	64.9480
30103.2100	65.0000	65.0390
. . .	. . .	. . .
30558.5200	65.0000	64.9480
30560.0000	26.4810	64.2460
30561.4800	-12.0380	58.7080
30562.9600	-50.5570	46.5790
30564.4500	-65.0000	27.4235
30565.9300	-65.0000	4.4850
30567.4100	-65.0000	-18.1935
30568.8900	-65.0000	-38.3175
30570.3700	-65.0000	-54.6650
30571.8500	-65.0000	-66.6185

Table 6.4 (Continued) Data table of PI control for position control test 1

Time (ms)	Position Command (Angle)	Position Feedback (Angle)
30573.3300	-65.0000	-74.3535
30574.8100	-65.0000	-78.3965
30576.3000	-65.0000	-79.6315
30577.7800	-65.0000	-78.8385
30579.2600	-65.0000	-76.6415
30580.7400	-65.0000	-73.8270
30582.2200	-65.0000	-70.9280
30584.9400	-65.0000	-66.5340
30586.4200	-65.0000	-64.8635
30587.9000	-65.0000	-63.7195
30589.3800	-65.0000	-63.1930
30590.8600	-65.0000	-62.9265
30592.3500	-65.0000	-62.9265
30593.8300	-65.0000	-63.2840
30595.3100	-65.0000	-63.5440
30596.7900	-65.0000	-63.8950
30598.2700	-65.0000	-64.2460
30599.7500	-65.0000	-64.5125
30601.2300	-65.0000	-64.7725
30604.2000	-65.0000	-65.0390

Other command is faster than first position command. This time command is 65 degree to -65 degree, 10 Hz, square wave which is shown on Figure 6.4. According to the position feedback data BLDC motor can trace also this command with PI Control.

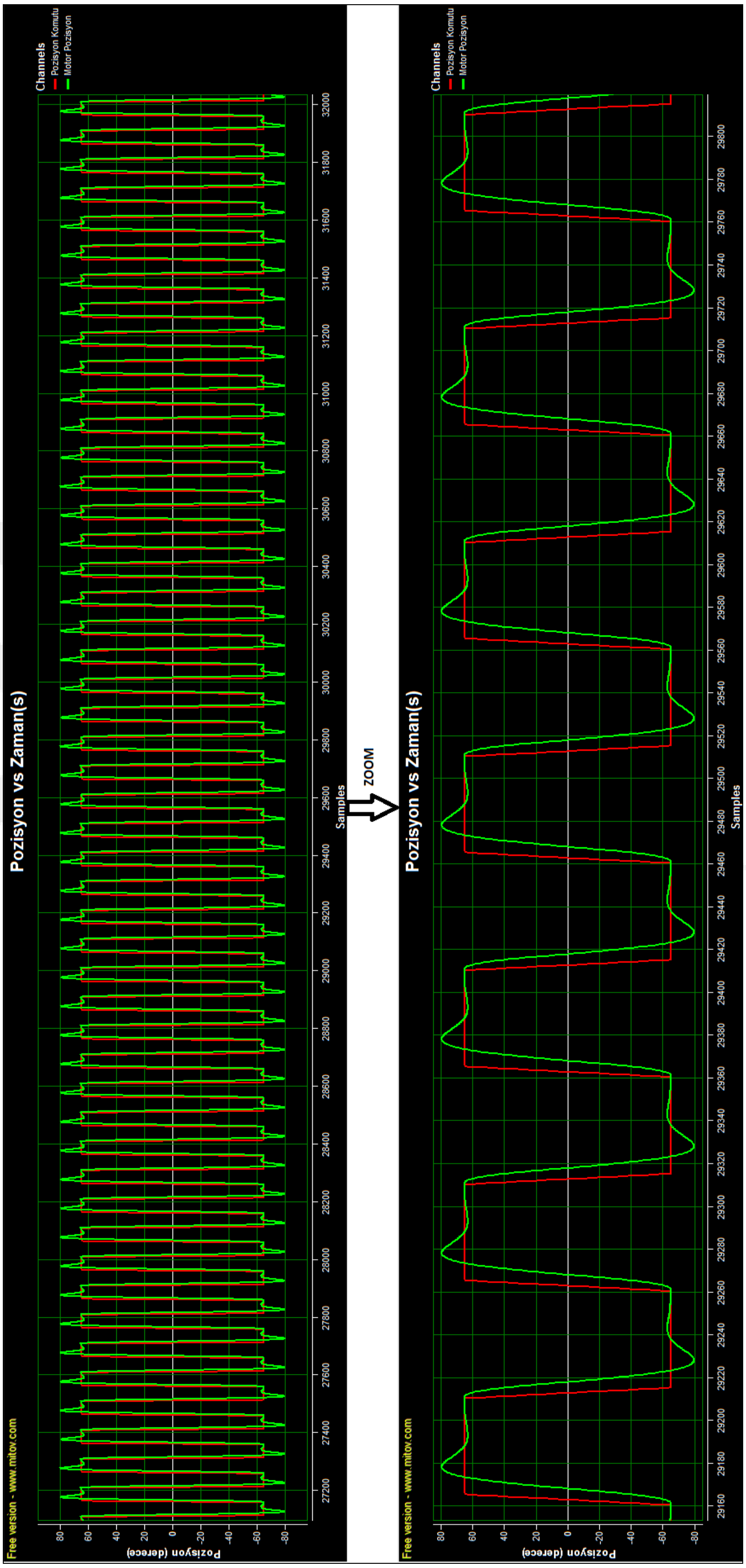

Figure 6.4 Experimental test results for PI control on position control test 2

Table 6.5 Data table of PI control for position control test 2

Time (ms)	Position Command (Angle)	Position Feedback (Angle)
29460.4900	-65.0000	-65.0390
29461.9700	-26.4810	-64.3370
29463.4600	12.0380	-58.8835
29464.9400	50.5570	-46.6700
29466.4200	65.0000	-27.4235
29467.9000	65.0000	-4.5695
29469.3800	65.0000	17.9270
29470.8600	65.0000	38.2330
29472.3500	65.0000	54.5805
29473.8300	65.0000	66.5340
29475.3100	65.0000	74.3535
29476.7900	65.0000	78.3965
29478.2700	65.0000	79.6315
29479.7500	65.0000	78.6630
29481.2300	65.0000	76.5505
29482.7200	65.0000	73.8270
29484.2000	65.0000	70.9280
29485.6800	65.0000	68.3800
29487.1600	65.0000	66.2675
29488.6400	65.0000	64.6880
29490.1200	65.0000	63.6350
29491.6100	65.0000	63.1085
29493.0900	65.0000	63.0175
29494.5700	65.0000	63.0175
29496.0500	65.0000	63.3685
29497.5300	65.0000	63.7195
29499.0100	65.0000	63.9860
29500.4900	65.0000	64.4215
29501.9700	65.0000	64.6880
29503.4600	65.0000	64.8635
29504.9400	65.0000	64.9480
29506.4200	65.0000	65.0390
29507.9000	65.0000	65.1300
29509.3800	65.0000	65.1300
29510.8600	52.1625	65.1300
29512.3500	13.6435	63.1930
29513.8300	-24.8755	55.6335
29515.3100	-63.3945	41.0475
29516.7900	-65.0000	19.8640
29518.2700	-65.0000	-3.2500
29520.9900	-65.0000	-41.3075
29522.4700	-65.0000	-57.0440
29523.9500	-65.0000	-68.2045
29525.4300	-65.0000	-75.3220

Table 6.6 (Continued) Data table of PI control for position control test 2

Time (ms)	Position Command (Angle)	Position Feedback (Angle)
29526.9100	-65.0000	-78.8385
29528.3900	-65.0000	-79.6315
29529.8800	-65.0000	-78.4875
29531.3600	-65.0000	-76.1150
29532.8400	-65.0000	-73.3915
29534.3200	-65.0000	-70.4860
29535.8000	-65.0000	-67.9380
29537.2800	-65.0000	-65.9165
29538.7700	-65.0000	-64.4215
29540.2500	-65.0000	-63.4595
29541.7300	-65.0000	-62.9265
29543.2100	-65.0000	-62.9265
29544.6900	-65.0000	-63.0175
29546.1700	-65.0000	-63.3685
29547.6500	-65.0000	-63.6350
29549.1400	-65.0000	-63.9860
29550.6200	-65.0000	-64.3370
29552.1000	-65.0000	-64.5970
29553.5800	-65.0000	-64.7725
29555.0600	-65.0000	-64.9480
29556.5400	-65.0000	-65.0390
29558.0300	-65.0000	-65.1300
29560.4900	-65.0000	-65.0390

6.2 Experimental Tests for Incremental Fuzzy Control Method

6.2.1 Current Control Test

The first experimental test for Incremental Fuzzy control method was current control test. The applied command is 1000 mA, 100 Hz, square wave which is shown on Figure 6.5. BLDC motor always can track the current command with Incremental Fuzzy control. There is no noise on steady state.

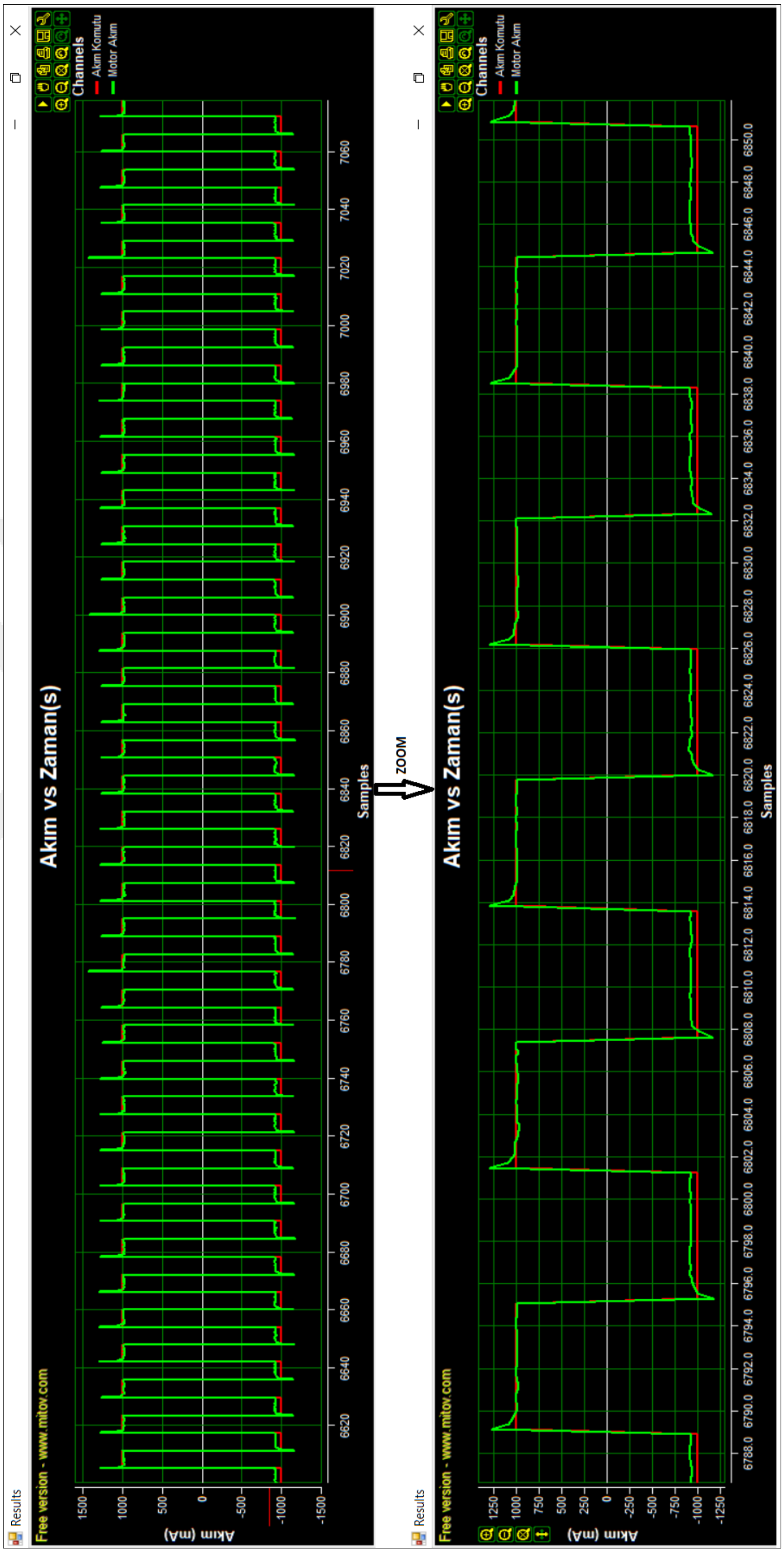

Figure 6.5 Experimental test results for Incremental Fuzzy on current control test

Table 6.7 Data table of Incremental Fuzzy control for current control test

Time (ms)	Current Command (mA)	Current Feedback (mA)
6813.4830	-997.3839	-926.5316
6813.7300	997.3839	441.4650
6813.9770	997.3839	1220.8420
6814.2240	997.3839	1040.9850
6814.4710	997.3839	1002.8340
6814.7180	997.3839	981.0334
6814.9650	997.3839	981.0334
6815.2120	997.3839	991.9338
6815.4580	997.3839	997.3839
6815.7060	997.3839	997.3839
6815.9530	997.3839	991.9338
6816.1990	997.3839	975.5832
6816.4460	997.3839	991.9338
6816.6930	997.3839	991.9338
6816.9400	997.3839	997.3839
6817.1870	997.3839	981.0334
6817.4340	997.3839	997.3839
6817.6810	997.3839	986.4836
6817.9280	997.3839	981.0334
6818.1750	997.3839	997.3839
6818.4210	997.3839	975.5832
6818.6680	997.3839	991.9338
6818.9160	997.3839	991.9338
6819.1620	997.3839	981.0334
6819.4090	997.3839	986.4836
6819.6560	-997.3839	-403.3137
6819.9030	-997.3839	-1155.4390
6820.1500	-997.3839	-991.9338
6820.3970	-997.3839	-948.3323
6820.6440	-997.3839	-921.0814
6820.8910	-997.3839	-926.5316
6821.1380	-997.3839	-915.6312
6821.3850	-997.3839	-904.7308
6821.6310	-997.3839	-921.0814
6821.8780	-997.3839	-921.0814
6822.1250	-997.3839	-915.6312
6822.3720	-997.3839	-926.5316
6822.6190	-997.3839	-921.0814
6822.8660	-997.3839	-910.1810
6823.1130	-997.3839	-910.1810
6823.3600	-997.3839	-915.6312
6823.6070	-997.3839	-921.0814
6823.8540	-997.3839	-926.5316

Table 6.8 (Continued) Data table of Incremental Fuzzy control for current control test

Time (ms)	Current Command (mA)	Current Feedback (mA)
6824.1010	-997.3839	-915.6312
6824.3480	-997.3839	-915.6312
6824.5940	-997.3839	-921.0814
6824.8410	-997.3839	-910.1810
6825.0880	-997.3839	-931.9817
6825.3350	-997.3839	-926.5316
6825.5820	-997.3839	-921.0814
6825.8290	997.3839	425.1145

Table 6.9 Some measurements of Incremental Fuzzy for current control test

Measurement	Value
Rise time	~0.2 ms
Settling time	~2 ms
Overshoot	%25
Steady state error(positive command)	-%3
Steady state error(negative command)	-%8

6.2.2 Position Control Test

The next experimental test for Incremental Fuzzy control method was position control test. Two different position commands were applied two BLDC motor by using electronic board. One of these commands is 65 degree to -65 degree, 1 Hz, square wave position command which is shown on Figure 6.6. According to the position feedback data BLDC motor can trace this command with Incremental Fuzzy control.

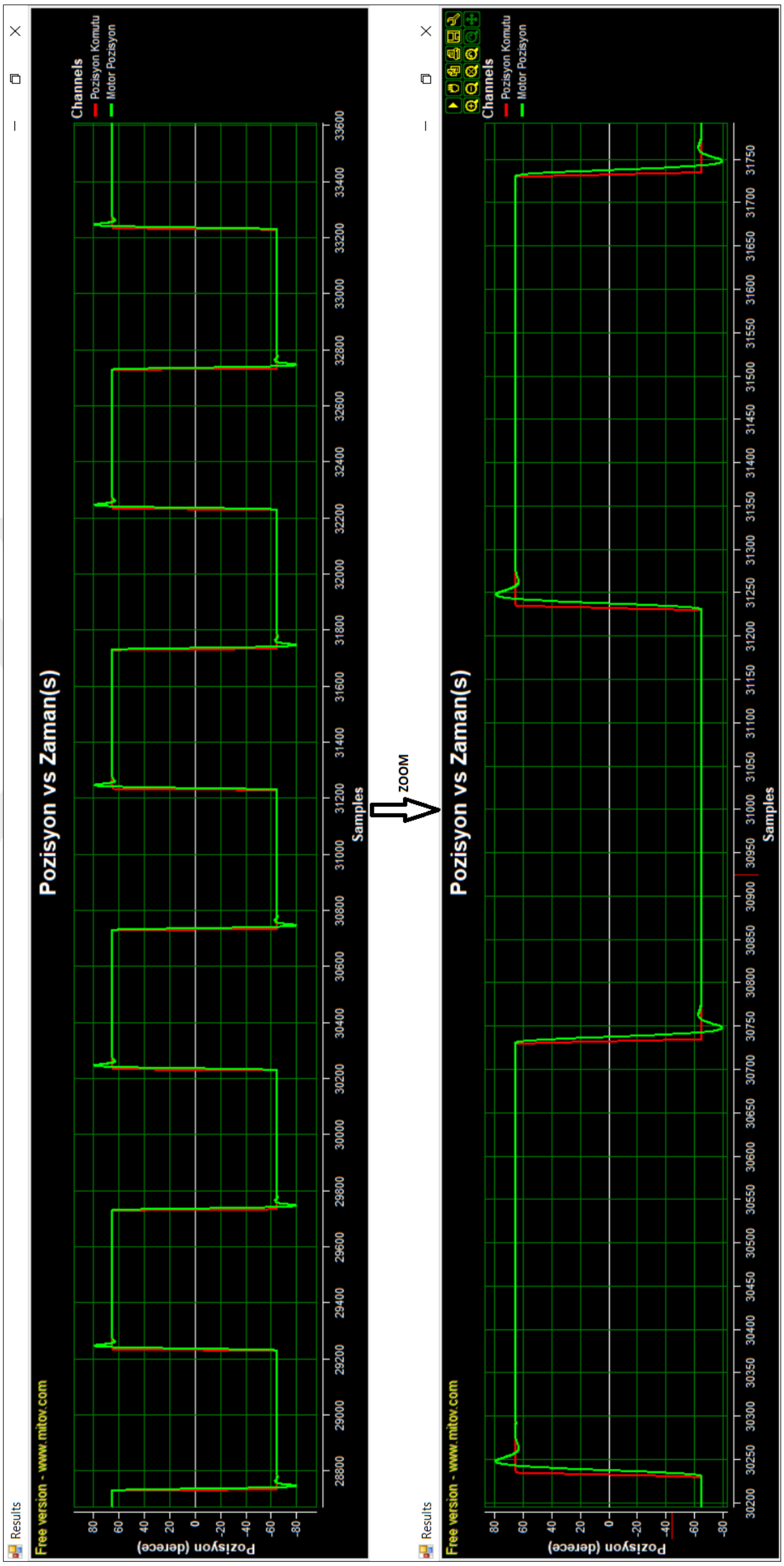

Figure 6.6 Incremental Fuzzy control test result for position control test 1

Table 6.10 Data table of Incremental Fuzzy control for position control test 1

Time (ms)	Position Command (Angle)	Position Feedback (Angle)
30231.2600	-65.0000	-65.0390
30232.7400	-26.4810	-64.1615
30234.2200	12.0380	-58.6235
30235.7100	50.5570	-46.5790
30237.1900	65.0000	-27.2480
30238.6700	65.0000	-4.5695
30240.1500	65.0000	18.1935
30241.6300	65.0000	38.2330
30243.1100	65.0000	54.6650
30244.5900	65.0000	66.5340
30246.0800	65.0000	74.3535
30247.5600	65.0000	78.3965
30249.0400	65.0000	79.7160
30250.5200	65.0000	78.8385
30258.1700	65.0000	76.6415
30259.6600	65.0000	73.9180
30261.1400	65.0000	71.1035
30262.6200	65.0000	68.4645
30264.1000	65.0000	66.2675
30265.5800	65.0000	64.5970
30267.0600	65.0000	63.5440
30268.5400	65.0000	63.9860
30270.0300	65.0000	64.2460
30271.5100	65.0000	64.5125
30272.9900	65.0000	64.7725
30274.4700	65.0000	64.9480
. . .	. . .	. . .
30731.5100	65.0000	65.0390
30732.9900	26.4810	64.2460
30734.4700	-5.6160	60.1185
30735.9500	-44.1350	49.3090
30737.4300	-65.0000	31.2000
30738.9200	-65.0000	8.5280
30740.4000	-65.0000	-14.3260
30741.8800	-65.0000	-34.9830
30743.3600	-65.0000	-52.0325
30744.8400	-65.0000	-64.6880
30746.3200	-65.0000	-73.2160
30747.8000	-65.0000	-77.7855
30749.2900	-65.0000	-79.3650
30750.7700	-65.0000	-78.7475
30752.2500	-65.0000	-76.8170

Table 6.11 (Continued) Data table of Incremental Fuzzy control for position control test 1

Time (ms)	Position Command (Angle)	Position Feedback (Angle)
30753.7300	-65.0000	-74.1780
30755.2100	-65.0000	-71.4545
30756.6900	-65.0000	-68.8155
30758.1700	-65.0000	-66.6185
30759.6600	-65.0000	-65.0390
30761.1400	-65.0000	-63.8950
30762.6200	-65.0000	-63.2840
30764.1000	-65.0000	-62.9265
30765.5800	-65.0000	-63.0175
30767.0600	-65.0000	-63.2840
30768.5400	-65.0000	-63.6350
30770.0300	-65.0000	-63.9860
30771.5100	-65.0000	-64.3370
30772.9900	-65.0000	-64.5970
30774.4700	-65.0000	-64.8635
30775.9500	-65.0000	-65.0390

Other command is faster than first position command. This time command is 65 degree to -65 degree, 10 Hz, square wave which is shown on Figure 6.7. According to the position feedback data BLDC motor can trace also this command with Incremental Fuzzy control.

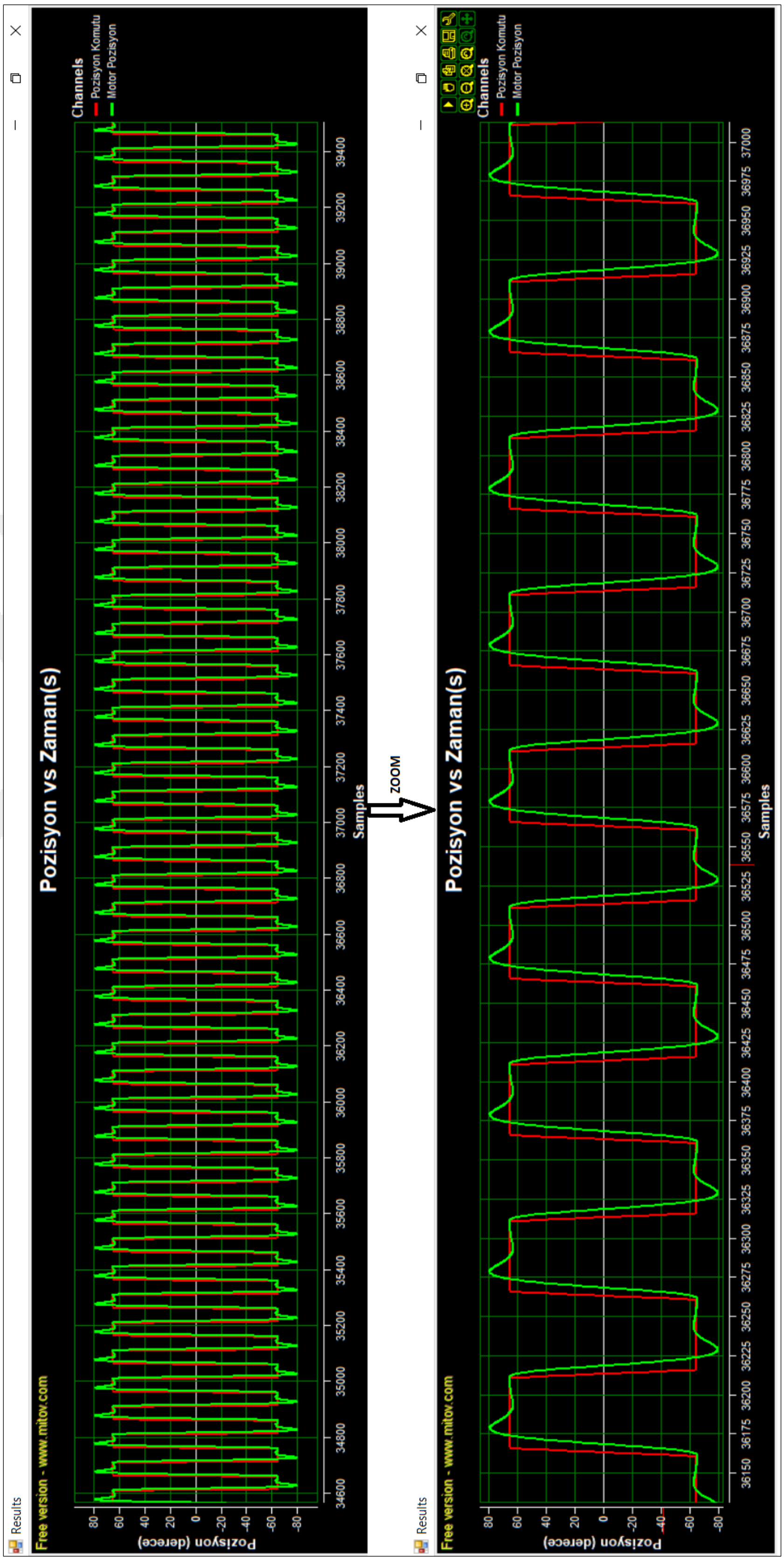

Figure 6.7 Incremental Fuzzy control test result for position control test 2

Table 6.12 Data table of Incremental Fuzzy control for position control test 2

Time (ms)	Position Command (Angle)	Position Feedback (Angle)
36558.4200	-65.0000	-65.1300
36559.9000	-26.4810	-64.4215
36561.3800	12.0380	-58.7080
36562.8700	50.5570	-46.4945
36564.3500	65.0000	-27.2480
36565.8300	65.0000	-4.4850
36567.3100	65.0000	18.1935
36568.7900	65.0000	38.3175
36570.2700	65.0000	54.7560
36571.7500	65.0000	66.7095
36573.2400	65.0000	74.4445
36574.7200	65.0000	78.4875
36576.2000	65.0000	79.7160
36577.6800	65.0000	78.8385
36579.1600	65.0000	76.6415
36580.6400	65.0000	73.9180
36582.1300	65.0000	71.1035
36583.6100	65.0000	68.4645
36585.0900	65.0000	66.2675
36586.5700	65.0000	64.5970
36588.0500	65.0000	63.5440
36589.5300	65.0000	63.0175
36591.0200	65.0000	62.8420
36592.5000	65.0000	62.9265
36593.9800	65.0000	63.2840
36595.4600	65.0000	63.5440
36596.9400	65.0000	63.9860
36598.4200	65.0000	64.2460
36599.9000	65.0000	64.5125
36601.3800	65.0000	64.7725
36602.8700	65.0000	64.9480
36604.3500	65.0000	64.9480
36605.8300	65.0000	64.9480
36607.3100	65.0000	65.0390
36608.7900	65.0000	65.0390
36609.0400	65.0000	65.0390
36610.5200	26.4810	64.3370
36612.0000	-12.0380	58.7990
36613.4800	-50.5570	46.6700
36614.9600	-65.0000	27.4235
36616.4500	-65.0000	4.3940
36617.9300	-65.0000	-18.0180
36619.4100	-65.0000	-38.3175
36620.8900	-65.0000	-54.4895

Table 6.13 (Continued) Data table of Incremental Fuzzy control for position control test 2

Time (ms)	Position Command (Angle)	Position Feedback (Angle)
36622.3700	-65.0000	-66.5340
36623.8600	-65.0000	-74.3535
36625.3400	-65.0000	-78.3965
36626.8200	-65.0000	-79.4560
36628.3000	-65.0000	-78.4875
36629.7800	-65.0000	-76.4660
36631.2600	-65.0000	-73.7425
36632.7400	-65.0000	-71.0125
36634.2200	-65.0000	-68.3800
36635.7100	-65.0000	-66.2675
36637.1900	-65.0000	-64.7725
36638.6700	-65.0000	-63.7195
36640.1500	-65.0000	-63.1930
36641.6300	-65.0000	-63.0175
36643.1100	-65.0000	-63.0175
36644.5900	-65.0000	-63.3685
36646.0700	-65.0000	-63.7195
36647.5600	-65.0000	-64.0705
36649.0400	-65.0000	-64.3370
36650.5200	-65.0000	-64.6880
36652.0000	-65.0000	-64.8635
36653.4800	-65.0000	-65.0390

CHAPTER 7

CONCLUSION

Improve the control of BLDC motor which is used on different parts of missile is aimed on this thesis. For this purpose, PI and Incremental Fuzzy control methods are compared for BLDC motor controlling by means of simulation and experimental results. In this way which one is better among these control methods is established by results of studies.

Simulation studies were performed on Matlab Simulink platform. PI control and Incremental Fuzzy control methods were analyzed by giving same position command on simulation. Simulation circuit for Incremental Fuzzy was generated by adding the Fuzzy block to PI control circuit. That is the only difference between two control method simulations. When we analyze the result graphics, we can observe undesired command and feedbacks of PI control are more than Incremental Fuzzy control. Especially when we focus at between 0.002 – 0.003 seconds on PI and Incremental Fuzzy simulation result graphics, we can see easily unwanted oscillation on current, speed, position graphics of PI controller. But there is any unexpected situation such as this oscillation on all graphics of Incremental Fuzzy control. According to these results of simulation Incremental Fuzzy control method is more stable and reliable than PI control method.

There are also experimental studies to compare the PI and Incremental Fuzzy control methods on this thesis. FPGA based electronic board was used for these experimental studies. Current and position command are sent to electronic board through Ethernet communication interface by using PC which is connected to electronic board with cable. Also current and position feedbacks are sent to PC by using this Ethernet interface. Thanks to control method which is implemented on FPGA, electronic board can control BLDC motor which is connected to electronic board with cable. Only implemented control method on FPGA is different for experimental studies of PI and Incremental Fuzzy control. The rest of the test setup is the same. The same current and position commands are applied to two different control methods. On current control test, Incremental Fuzzy control method is obviously better than PI control method. There are so many unexpected current feedbacks such as 0 and 1600 mA for 1000 mA current command on PI control. These feedbacks are unwanted for controller. On Incremental Fuzzy control, there is none unexpected current feedback such as shown on PI control. Also rise time, settling time, overshoot and steady state error for positive command are the same both PI and Incremental Fuzzy control. Only steady state error for negative command of Incremental Fuzzy control is worse than PI control. There are also position control tests for two different controllers. Performances of the controlling BLDC motor both PI and Incremental Fuzzy control methods are the same on position control tests. Both controllers can trace the position commands. These experimental studies again prove that Incremental Fuzzy control method is better than PI controller.

So with regard to both simulation and experimental results, Incremental Fuzzy control method is more successful, reliable and stable than PI control method. Implementation of Incremental Fuzzy control instead of PI control will improve the performance of missiles.

In order to increase the performance of Incremental Fuzzy control, recommended future works are listed below:

- Classification of the inputs of Incremental Fuzzy control can be more generic. Border which depends on command can be used instead of constant border for classes.
- Steady state error for negative command was higher than PI controller on the experimental current tests. Some improvements can be found to reduce this error.
- Experimental tests were applied to unloaded BLDC motor. These tests can be applied also loaded BLDC motor.

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CURRICULUM VITAE

PERSONAL INFORMATION

Name Surname: Murat ÖZEV

Date of Birth: 02.01.1992

Phone: 5387330392

E-mail: murat_ozev92@hotmail.com

EDUCATION

High School: Denizli Lütfi Ege Anadolu Öğretmen Lisesi

Bachelor: Hacettepe

WORK EXPERIENCE

Digital Electronic Designer at TUBITAK SAGE 4.5 years

TOPICS OF INTEREST

BLDC Motor Control

FPGA Code Design

Electronic Board Design